WITHIN- AND BETWEEN-TREE VARIATIONS IN THE WOOD QUALITY OF RADIATA PINE

A THESIS

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By

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ABSTRACT

This study was conducted to determine the within- and between-tree variations in the physical and mechanical properties of Pinus radiata (radiata pine).

Forty eight trees from a 25-year-old plantation on the Canterbury plains near Dunsandel in the South Island of New Zealand were felled and cross-cut to give three 3.6 meter logs. Each log was identified by tree number and position up the height of the tree (butt, middle and top log).

At the sawmill the logs were sawn, first by removing 40 mm thick slices known as flitches from opposite sides of the trunk until a 100 mm thick plank known as a cant was left at the centre. The flitches were re-cut at the breast bench circular saw to yield timbers of nominal dimensions 100x40 mm. In re-cutting the 100 mm wide cant gave 3 - 5 boards depending on the diameter of the log. The position of every board was recorded relative to the pith and numbered. A total of 915 boards from the 48 trees (144 logs) were obtained. The boards were filleted (i.e. stacked with uniform and sufficient spacing between each layer both in the vertical and horizontal directions so as to ease air circulation) and air-dried to approximately 12% moisture content.

After drying the boards were dressed to 90x35 mm and grouped into one of the four Australian structural grades (F4, F5, F8 and F11) as each board passed through a stress grading machine.

The modulus of elasticity of the boards was measured both in flatwise bending and axial tension. The strength of the boards was determined by destructive testing in tension and compression parallel to the grain.

After failure in tension short clear planks (i.e. planks with no knots and any other natural defects) were cut from each board. From these short planks small clear specimens were prepared for the determination of stiffness, bending strength and compression strength parallel to the grain.

The investigation of density, stiffness and strength in relation to the vertical and radial positions within a tree revealed that there is a significant variation in all properties with changes in radial positions across the diameter, and a significant variation in strength properties, but not stiffness with change in vertical position up the height of the tree. Regarding between-tree variation, all properties changed significantly.

With reference to the production of structural framing timber, stiffness and density were compared as criteria for sorting trees and identifying superior material within logs. This analysis revealed that stiffness is a better criterion for selecting superior trees within the natural population of a forest stand, to improve the value of mill production and to achieve a better outturn in higher value grades (F5 and above).

A regression analysis between the properties of the in-grade timber and clearwood showed that there is a very strong relationship between the modulus of elasticity of clearwood and that of the in-grade timber.

As expected there was a general decrease in strength and stiffness of the graded timber as the grade value decreased from F11 to F4.

Strength and stiffness values in tension, bending and compression have been compared with the current New Zealand, Australian and European code design values, generally giving good recovery of higher value grades (F5 and above), especially for strength.

CHAPTER 1: **INTRODUCTION**

1.1 **General**

1.1.1 **Wood**

Wood is defined by Webster and McKechnie (1980) as the hard fibrous substance beneath the bark in the stems and branches of trees and shrubs. More explicitly Larson (1969) stated that wood is the xylem of a tree, produced at the cambium and consists of cells that have passed through various stages of development. All the development phases of cellular division, differentiation, and maturation taken together constitute wood formation. However, Zobel and Buijtenen (1989) argue that no specific definition of wood is totally satisfactory.

Regardless of definition, wood is a remarkable material with such variability and flexibility that makes it useful for many kinds of products (Zobel and Buijtenen, 1989). Its composition of cellulose, hemicelluloses, lignin, numerous types of extractives, sugars, and other organic and inorganic substances produce a raw material that can be used for many things, including papers, building materials, chemicals, energy, and even food (Domio, 1984).

Zobel and Buijtenen (1989) report that it is important to understand that wood is complex and variable, consisting of numerous substances that are organised in different ways, with the result that wood is a very nonuniform material. Differences occur among species and genera, among geographic sources within a species, among trees within a geographic source as well as between and within individual trees.

According to Zobel and Buijtenen (1989) although the variability of wood gives it great utility it is also a major drawback to its efficient use as a raw material. Keating (1983) stated that the variability of wood is not only one of its attractions but is also the reason why we have never been able precisely to catalogue and predict its performance. The uniformity so greatly desired by manufacturers and users is lacking in wood, resulting in variation in quality and thus in production inefficiency. Indeed, the greatest wood quality problem facing all wood-using industries is its lack of uniformity (Larson, 1969).

1.1.2 **Wood properties and wood quality**

Concerning the concepts of **wood properties** and **wood quality**, Zobel and Buijtenen (1989) report that wood properties are easily defined but their utilisation value, i.e. quality, varies according to product and utilization standard. It is impossible to find a totally satisfactory meaning for wood quality as many disagreements arise, because wood quality can have meaning only when the final product is known.

Many wood scientists refer to wood properties in terms of the cellular, anatomical, and chemical characteristic of the wood within and among trees (Zobel and Buijtenen, 1989). Wood quality relates to the cumulative effect of these wood properties on some specified product or products. Unfortunately, in every usage the terms wood property and wood quality are used interchangeably. There are references where wood properties referred to the strength of the wood rather than to its anatomy or chemistry. Because of differing uses the reader should take the context the writer uses the terms: wood properties and wood quality.

A detailed literature review on the subject of wood quality/property variation is presented in Chapter 2.

The importance for research into the wood quality variations, their control, and their effect on the quality of the wood products is emphasized by nearly every author. The subjects most widely examined are the variability within and among trees. In both cases variability is great and provides opportunities to the forest grower to develop better wood, especially since the inheritance of wood properties is usually strong. Silvicultural practices can also influence wood properties.

1.1.3 **Variability**

There are several patterns of variability within trees that are of importance. The first is the within-ring differences, the second the changes from centre of the tree to the outside, and the third the differences associated with variations with height up the tree. Within-tree variability is very large with greater variation in wood characteristics within a single tree than among trees growing on the same site or between sites (Larson, 1969).

Further, between-tree variation is so large for all species that it makes studies of wood difficult and utilization inefficient. If between-tree variation is not recognized and accounted for, large errors will be made in wood property studies or in predicting strength and quality of products in wood utilization (Zobel and Buijtenen, 1989).

The current research programme investigates variations in mechanical properties of timber both within and between radiata pine (Pinus radiata) trees which is the most important commercial species in New Zealand.

1.2 An overview of the research programme

Comparative studies between radiata pine and favoured timbers of the Northern Hemisphere indicate that the mechanical properties of radiata pine fall short of those of commercially important species of the Northern Hemisphere (Walford, 1991): of the eleven species examined radiata pine was ranked 7/11 in strength and only 11/11 in stiffness. Radiata pine also displayed the lowest stiffness to strength ratio. Moreover, previous studies at the University of Canterbury (Addis Tsehaye, 1989; Hadi, 1992) have identified poor stiffness characteristics of corewood and its variability between regions of the South Island. An analysis of stiffness, bending strength and tensile strength of machine stress graded boxed-pith timber from Nelson and similar analysis of corewood from Canterbury Plains showed that the Canterbury timber had 60 percent of the tensile strength, but only 40 percent of the stiffness of comparable Nelson material .

The issue is accentuated by forest growers pruning the butt log to achieve better financial returns from the clearwood, as potential material for the framing and structural markets can come only from the poor quality corewood/juvenile wood (adjacent to the pith) of the butt log and the unpruned knotty logs further up the stem. The situation is aggravated by short-rotations (<30 years) as little high density outerwood will be produced. However, some 50 percent of the stands have not been pruned and thinned at the correct time and some unpruned outerwood from the butt logs of these stands could become available for structural uses.

Wood of superior quality (however defined) is less susceptible to the vagaries of markets, offering greater flexibility and fitness for various uses. Within this context the emphasis of this thesis is centred on improving timber for structural purposes, and especially its stiffness. This in turn requires an understanding of the causes of its variability both in the unpruned part of the butt log and further up the stem.

One approach to improved structural properties is to cut out the worst knot(s) and finger joint. This will increase the strength of timber by approximately 25 percent (Addis Tsehaye *et al.* 1992). Unfortunately stiffness is insensitive to this approach (ibid.) and can be improved only by further processing such as laminating. Laminating allows the mixing of high and low stiffness pieces to produce a member having properties that more closely resemble the mean properties of the population. This is still not ideal as the mean stiffness of radiata pine compares unfavourably with foreign timbers.

The above situation shows the importance of detailed research that aims at improving timber quality for structural purposes. This would involve an analysis of the variations in mechanical properties of timber both between and within trees (by log type - butt, second, third, top log, and within the log itself - from pith to cambium). Such a study would demonstrate the potential benefits of selecting trees with specific, predictable and above-average wood qualities (between-tree variations) and would also delineate where structural timber is most likely to be recovered within a tree (within-tree variations).

1.3 **Goals of the research programme**

The overall goals of the research programme are:

1. To seek technologies which better identify and select superior material within logs, with particular emphasis on the framing and structural markets;

2. To determine the improvement in the grade outturn (i.e. comparison in the proportion of F5 above with that of F4 and below) that could arise from the selection of stiffer trees within the natural population of the forest stand; and

3. To determine whether there is a correlation between the mechanical properties of timber and that of clearwood (with both standard- and micro-sizes). A significant

relationship between the mechanical properties of timber and clearwood would be very important for subsequent studies into the relationships between the stiffness of wood and corresponding wood quality characteristics (i.e. density, compression wood, chemical composition, microfibril angle, cellulose quantity and quality and spiral grain), so that the fundamental parameters most influencing stiffness can be identified and considered for genetic manipulation.

In this thesis, the mechanical and physical properties of kiln dried, machine stress and visually graded radiata pine timber are determined by destructive testing, first as graded timber and then by cutting into clearwood samples (i.e. samples with no knots and any other natural defects).

1.4 **Organization**

1.4.1 **In-grade testing of timber from whole trees**

In this experiment the tensile and compressive strength, stiffness, and density of sawn timber cut from the whole trees will be determined. The aims of this experiment are:

(a) To measure the differences in the physical and mechanical properties of timber cut from various log types (butt to top log) and describe the gradual changes from pith to the cambium, and to determine the between-tree variation in the physical and mechanical properties of timber;

(b) To estimate the lower end of the strength distribution (i.e. the 5th percentile values) and the mean values of stiffness, and hence determine the characteristic stresses of the material on the basis of log type and within the log in moving from pith to the cambium;

(c) To investigate the appropriate regression equation of strength on stiffness for the research material; and

(d) To address some of the fundamental issues in timber engineering, eg. the relative strength of timber in tension and compression, and the influence of factors such as grade, density and spiral grain on these properties.

1.4.2 **Testing of standard size clearwood samples**

In this experiment the bending and compressive strength, stiffness, and density and spiral grain of standard size (20x20x300 mm) clearwood specimens cut from each board (from the in-grade testing experiment above) will be determined. The aims of this experiment are:

(a) To determine if there is a correlation between the mechanical properties of timber and clearwood, cut from the same logs (butt, second and third logs) and exactly the same positions (pith to cambium);

(b) To test whether the same superior trees (i.e. the stiffer trees within the natural population of the stand, selected on the basis of the in-grade testing programme) will be selected in the clearwood testing programme.

1.4.3 **Testing of "matchstick" specimens**

This part of the project is beyond the scope of the thesis work. It is outlined to indicate the manner in which the study will develop in the future and to place the Ph.D programme in context.

The main aim of this experiment will be to determine whether there is a correlation between the stiffness of timber with that of clearwood at the cellular level.

In this experiment the stiffness and compressive strength of wood will be measured using 1x1x4 mm "matchstick" samples. Three trees at either extreme of stiffness will be selected for detailed wood quality assessment (in Experiment 2 above), with matchstick samples being cut from the standard small clearwood specimens. Provisionally both earlywood and latewood material will be tested. The matchsticks will be used to explore the relationships between the stiffness of wood and corresponding wood quality characteristics (i.e. density, compression wood, chemical composition, microfibril angle, cellulose quantity and quality and spiral grain), so that the fundamental parameters most influencing stiffness can be identified and considered for genetic manipulation.

CHAPTER 2: **REVIEW OF LITERATURE**

2.1 **WOOD QUALITY VARIATIONS**

Variations in wood quality are attributed to variations within a tree (i.e. variations within individual growth rings, between successive growth rings and with height up the stem), variations between trees within a single uniform stand and variations between populations of the same genotype growing in different geographic regions.

2.1.1 **General Introduction**

In subsequent sections the literature will be reviewed concerning the anatomical, physical, mechanical and chemical properties of wood such as fibre length, microfibril angle, spiral grain, reaction wood, density, stiffness and strength. The review will focus on the major causes of wood quality variation (within trees, between trees and between sites) in softwood species, giving much emphasis to radiata pine.

2.1.2 **Within-tree variations**

As a broad generalisation, during the last 40 - 50 years within-tree variation has been the dominant theme of wood quality research in many countries by many scientists. Walker (1993), in a review of basic density, reported that the within-tree variations exemplified by the hard pines and medium-to-high density diffuse porous hardwoods have received particular attention as many important plantation species fall into these groups.

2.1.2.1 **Variations within annual growth layers**

Before examining the variability within annual growth layers, it is appropriate to give a brief overview of the anatomy of the secondary wall of softwood tracheids as this is a most important feature in determining the properties of wood. Preston (1974, p.277) gives the following description of the secondary wall:

> "The secondary wall is divided into three layers, first named by I.W.Bailey, "S_1", "S_2" and "S_3". The letter "S" is shorthand for secondary and implies

that all three layers are secondary, a view strongly held on the grounds of anatomy. The difference among these three layers is due to differences in microfibril orientation. The S_2 layer varies considerably in thickness. In the wood laid down by the tree late in the season - the late or summerwood - is considerably thicker than either the S_1 or S_3 and often thicker than both taken together. In early or spring wood it is very much thinner and may then be thinner than the S_1 or S_3".

Even with regard to earlywood Preston's final statement appears rather extreme as typical figures for the thicknesses of the S_1 and S_3 layers are of the order of 0.1 - 0.2 µm, whereas even with earlywood the S_2 layer is typically 1 - 2 µm (Walker, 1993). However, in the case of earlywood in juvenile wood, especially in the first year or two of growth the relative significance of S_2 will be less than in more mature wood.

The secondary wall is surrounded by a thin primary wall, with randomly orientated webs of microfibrils, and the lignin-rich middle lamella (Preston, 1974).

Harris (1981) in his report on variability of wood quality, stated that the most striking feature of variability in wood often derives from the division of each annual growth layer into earlywood (EW)) and latewood (LW), which in the light of Preston's observations must reflect the relative dominance of the S_2 in latewood as compared to the situation in earlywood.

2.1.2.2 **Variations between successive growth layers**

The major source of variation between growth layers is that occurring between corewood and outerwood.

Juvenile wood (corewood) is classified as that portion of the xylem surrounding the pith in a cylindrical column (Figure 2.1) whose cells have not reached the dimensions found in mature (outer) wood (Smith and Briggs, 1986).

There is no clear-cut demarcation between juvenile wood (corewood) and mature wood (Senft *et al.*, 1985). Isebrands and Huns (1975) and Dinwoodie (1981) agree that corewood includes the first 5 to 20 rings with the transition point depending primarily on species and wood properties under consideration. Juvenile wood is being laid down in the upper portion of the tree even though the lower bole of the tree may have been forming mature wood for some years.

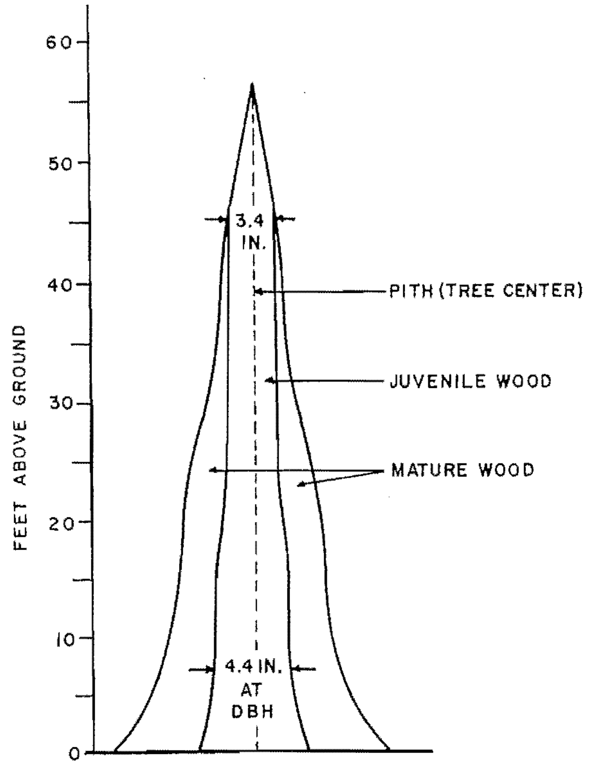


Figure 2.1 **Distribution of juvenile wood in a tree stem (from Zobel and van Buijtenen, 1989).**

Bendtsen (1978) provided a popular characterisation of the properties of juvenile wood. He noted that the properties of juvenile wood are not uniform from the pith outwards. The wood in the first formed rings has the lowest specific gravity (density), shorter fibres and larger microfibril angles. In successive rings from the pith, the specific gravity is greater, fibres become longer and microfibril angle smaller. The rate of change in most properties is very rapid in the first few rings; the later rings gradually assume the characteristics of mature wood (Figure 2.2)

According to Bendtsen (1978), compared to mature wood, juvenile wood of conifers is characterised by low specific gravity, shorter tracheids, larger microfibril angle, lower transverse shrinkage, higher longitudinal shrinkage, lower strength, lower percentage of latewood, more compression wood, higher moisture content, thinner cell walls, smaller lumen diameter, lower cellulose content but higher lignin content, and it has also a relatively dull and lifeless appearance.

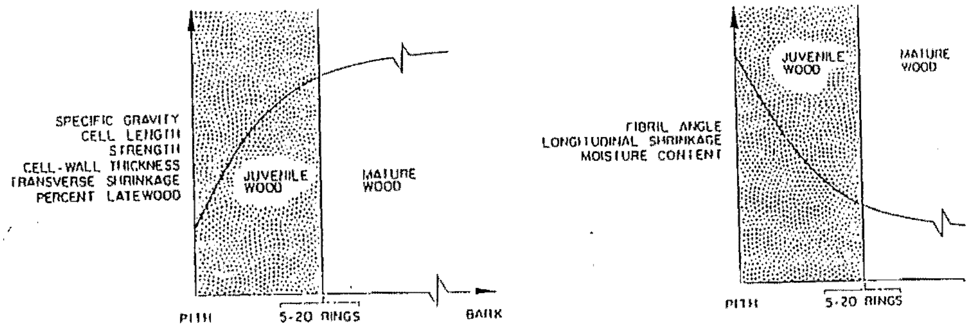


Figure 2.2 **Schematic representation of the gradual change in properties from juvenile wood to mature wood in conifers (from Bendtsen, 1978)**.

The problem of weaker mechanical properties of juvenile wood was noted by Koch (1966), when involved in research to develop straight studs from Southern pine peeler cores. He found that most studs had lower bending strength and stiffness than expected. Later Moody (1970) and Gerhards (1979) observed a 50 percent reduction in strength with pith-associated material (note that the term, pith-associated, means juvenile wood near the pith which can be pith-free).

Wu and Wang (1988) in their study of wood properties of Acacia magium and A. auriculiforms, reported that fibre length, specific gravity, cell wall thickness, transverse shrinkage and strength and stiffness initially show low values near the pith, which increase from pith to bark; in contrast the microfibril angle and longitudinal shrinkage initially have high values near the pith, which decrease from pith to bark.

2.1.2.3 **Variations up the stem**

The third source of within-tree variation is that occurring at different heights in a tree. This variation is primarily a function of the proportion of corewood up the height of the tree.

Walker (1993) observed that basic density decreases and moisture content increases on moving up the stem. He explained further that such behaviour should not be surprising in view of the steep radial basic density gradient in the vicinity of the pith, since the wood further up the stem must have proportionately more corewood.

2.1.3 **Variations between-trees growing on similar sites**

The variation between apparently similar trees growing within a uniform site is a major source of variation. Walker (1993) reported that regardless of species or where the forests are established the variation in wood properties between trees is very great. The between-tree differences are assumed to reflect the high level of genetic variation within the population. Harris (1981) commented that the larger part of this between-tree variability may be under genetic control, and it is, therefore, the source of potential improvements by selective tree breeding.

Dadswell *et al.* (1961) made the following statement about the between-tree variations among radiata pine trees growing in Australia and New Zealand:

> "A striking feature of radiata pine growing in Australia and New Zealand is the great variation in the external, morphological characteristics. This variation is due to differences among the various trees resulting from two factors: heredity and environment. Heredity plays a very important role is obvious to any observer visiting a plantation of clones. He is immediately struck as much by the large differences between clones as by the uniformity within each clone. Characteristics such as height, stem girth, stem taper, crown diameter, angle of branching and bark thickness can be improved by proper genetic selection".

2.1.4 **Variations between-sites**

The importance of variability between populations of the same species growing in different sites (Zobel and van Buijten, 1989) is summarised by Walker (1993, p.166):

> "Natural selection does not operate on averages but on extremes. It is the extreme frosts rather than the mean annual temperature that matter, and it is

the distribution and periodicity of rainfall rather than the mean annual figure that matter. Fortunately trees are amongst the most variable of all living organisms: selection can be very effective from a large, broad-based, moderately well adapted population, selecting the best trees from the best unrelated families to ensure a broad base of unrelated individuals having superior characteristics".

2.2 **RADIATA PINE**

Radiata pine is the most important plantation species in New Zealand, and generally in the Southern Hemisphere. Timell (1986) reported that radiata pine is widely planted throughout the Southern Hemisphere because of its exceptionally high growth rate and other superior characteristics. At that time, New Zealand and Chile were estimated to have 700000 ha. each planted with radiata pine, followed by Australia with 480000 ha. The current figure for the New Zealand plantations is 1.2 million ha. (NZFOA, 1994).

Concerning the current source of wood in New Zealand, Buchanan (1986) reports that until very recently much of the current production of wood in New Zealand has been from 50 - 60 year old trees planted in the 1930's whereas in the immediate future production will be from smaller trees only 20 - 30 years old. The average strength and density are lower in the younger "new crop" trees, and the intrinsic wood properties and defects are often quite different.

Early work by researchers in Australia including Langlands (1938), Wardrop (1951), Dadswell and Wardrop (1959) and Kloot (1957) have shown that there are within-tree variations (i.e. variations within individual growth rings, between successive growth rings and with height up the stem), variations between trees within a single uniform stand and variations between populations of the same genotype growing in different geographic regions in radiata pine. More recently the effect of these sources of variation in radiata pine grown in New Zealand has been reported (Cown, 1980; Cown and McConchie, 1980, 1983; Cown *et al.*, 1991a; Harris, 1981; Walford, 1985; Donaldson, 1992). Both the Australian and New Zealand work are discussed in detail below.

2.3 **ANATOMICAL PROPERTIES**

2.3.1 **Microfibril angle**

The microfibril angle is the angle between the helically wound cellulose microfibrils in the middle (S_2) layer of the secondary wall of the tracheid and the longitudinal cell axis (Dadswell and Wardrop, 1959).

Walker (1993) reported that microfibril angle in the corewood has an enormous effect on wood properties, and in particular very strongly determines the stiffness of wood within the first 20 growth rings from the pith. The effect of the microfibril angle on the mechanical properties has been well documented (Dadswell and Wardrop, 1959; Cave, 1969; Meylan and Probine, 1969).

The microfibril angle is important in determining the strength properties of individual fibres. Thus there is a definite relationship between microfibril angle and the tensile strength of individual fibres, a small microfibril angle being correlated with high tensile strength (Dadswell and Wardrop, 1959).

Cave and Walker (1994) extensively reviewed the influence of microfibril angle on the stiffness of wood. They noted that Cowdrey and Preston (1966) had observed a sixfold increase in stiffness in the earlywood of Picea sitchensis as the microfibril angle decreased from 40 degrees to 10 degrees; Cave (1969) reported a fivefold increase in stiffness in the earlywood of Pinus radiata as the microfibril angle decreased from 40 degrees to 10 degrees (Figure 2.3); Bendtsen and Senft (1986) also observed a fivefold increase in stiffness over the first 30 growth rings for P. taeda. Concerning the change in specific gravity (density), Bendtsen and Senft (1986) reported that the change in specific gravity with age was quite modest, amounting to only about 40 percent from growth rings near the pith to those near the cambium. They deduced that this increase in specific gravity was not sufficient by itself to account for the increases observed in the stiffness properties for the species.

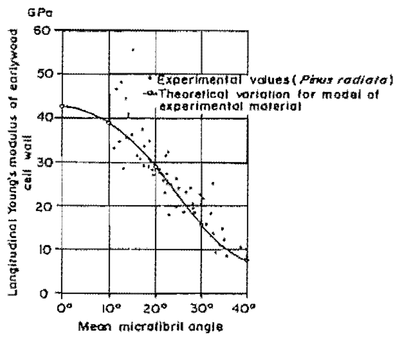


Figure 2.3 **Relationship between mean microfibril angle and longitudinal Young's modulus of cell wall material, derived from earlywood of *Pinus radiata radiata* taken from two discs approximately 30 growth rings (from Cave and Walker, 1994).**

In reviewing work by Cowdrey and Preston (1966), Cave (1968), Meylan (1972) and reanalysing that of Bendtsen and Senft (1986) above, Cave and Walker (1994) emphasised that despite the traditional belief that density determines mechanical properties, the only known physical characteristic of wood which is capable of effecting large changes in stiffness of wood is the cellulose microfibril angle in the S_2 layer of the tracheid cell wall.

Microfibril angle also plays a very important role during the seasoning of wood. Bendtsen (1985) explained that microfibril angle is largely responsible for the difference in shrinkage between corewood and mature wood. As wood dries water is removed from between the microfibrils. The microfibrils respond by moving closer together. When the microfibrils lie at large angle to the longitudinal axis of the cell as in corewood this causes a larger than normal shrinkage in the longitudinal direction compared to mature wood, and a lower than normal shrinkage in the transverse directions.

Harris and Meylan (1965) in their study of the influence of microfirbril angle on longitudinal and tangential shrinkage in P. radiata, showed that the relationship between longitudinal and tangential shrinkage and the mean microfibril angle in the S_2 layer were complex and curvilinear.

The longitudinal and tangential shrinkage curves are observed to intersect at about 50 degrees microfibril angle (Figure 2.4). This cross over value is dependent to a certain extent on the cell wall thickness and lies between 45 and 50 degrees microfibril angle. This pattern of shrinkage is a general phenomenon in all softwoods. Also, Harris and Meylan showed that longitudinal shrinkage is negligible when the microfibril angle is less than 25 to 30 degrees but as the angle increases above this figure there is a very rapid increase in longitudinal shrinkage on drying. In the first few growth rings, adjacent to the pith, the longitudinal shrinkage of many softwoods is very high and may exceed the tangential shrinkage simply because the microfibril angle is large in that region.

Within a tree the microfibril angle changes with tracheid length over successive growth layers (Wardrop and Preston, 1950), the angle being least in the longest tracheids. Because of this correlation microfibril angle is indicative of cell length and as such gives some information on the position of the tree from which the fibres are derived (Dadswell and Wardrop, 1959).

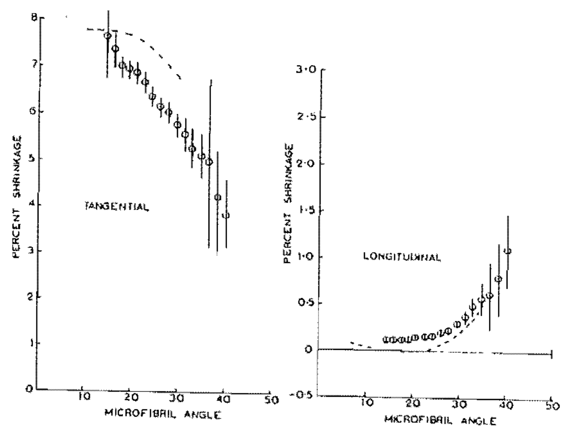


Figure 2.4 **The relationship between the oven-dry shrinkage of latewood and microfibril angle (from Harris and Meylan, 1965).**

Donaldson (1992) examined within-tree and between-tree variations in microfibril angle for four radiata pine trees from Kaingaroa Forest. Concerning the within-tree variation, he observed that mean microfibril angle in the first five growth rings declined from 45 degrees at the butt, to 38 degrees at 1.4 m, to around 26 degrees between 7 and 30 m high (Figure 2.5a). In the case of between-tree variations, he reported that for the four trees, generally, the microfibril angle ranged from about 15 to 23 degrees for outerwood, and 18 to 36 degrees for corewood (Figure 2.5b).

2.3.2 **Tracheid length**

The average cell length is another general indicator of wood strength particularly in tension parallel to the grain. The shorter tracheid length observed in fast-grown conifers implies lower tensile strength (Senft *et al.*, 1985).

Tracheid length is important for strength in that there will be a minimum length below which there is insufficient overlap to permit the transfer of a given stress without failure in shear intervening (Dinwoodie, 1981). This research revealed that there is a high degree of correlation between the length of the cell and the strength of the cell wall material.

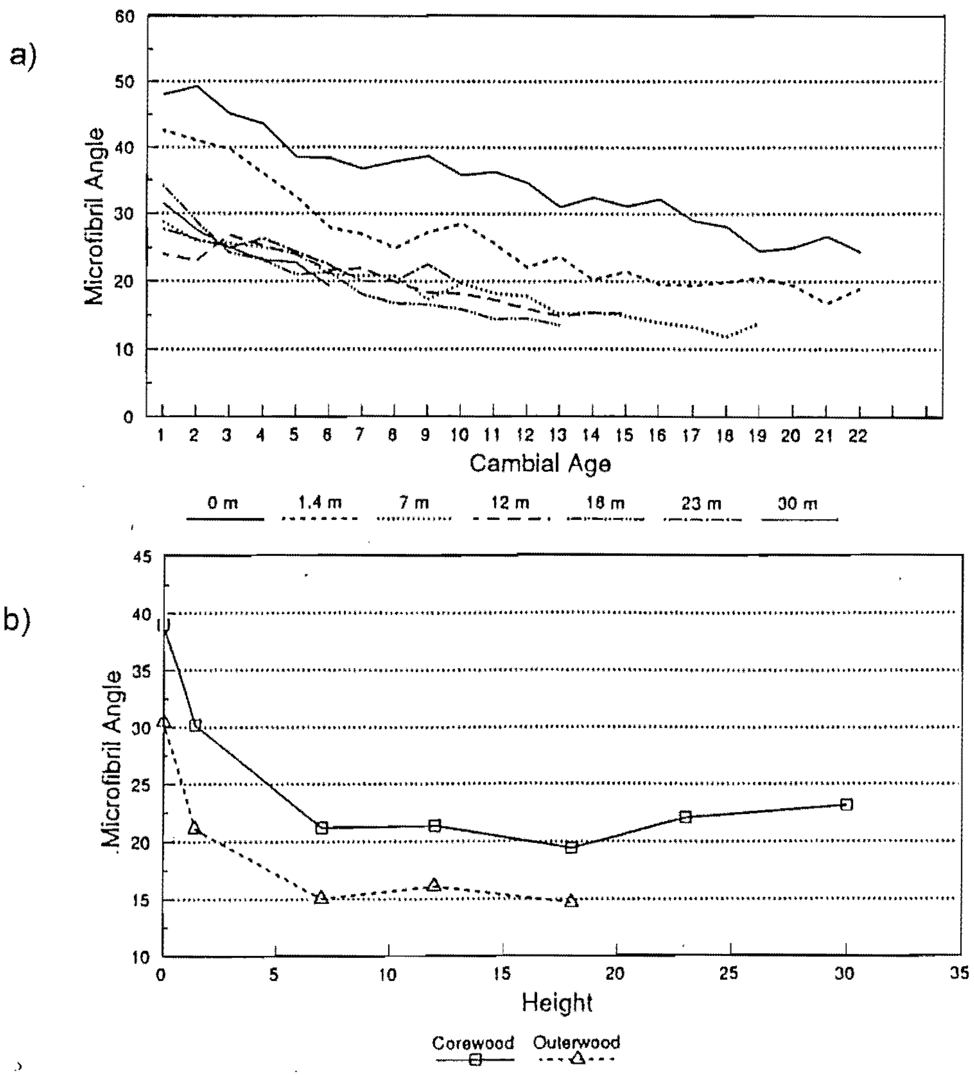


Figure 2.5 **Variation in mean microfibril angle (a) with cambial age and height and (b) among trees at breast height (from Donaldson, 1992).**

Concerning the between-tree variation of tracheid length, Dadswell and Wardrop (1959) stated that the average tracheid length in the first growth rings of one tree is not always identical with that in another tree of the same species. In some cases it can be as much as twice as great and this difference is maintained through successive growth layers (Figure 2.6).

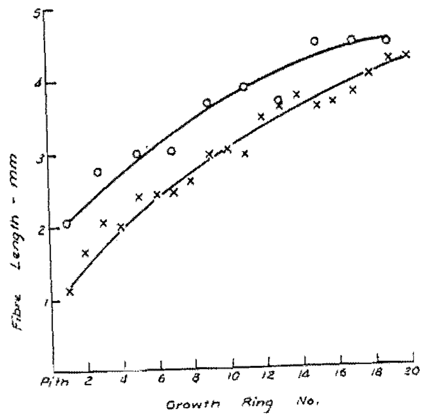


Figure 2.6 **The increase in tracheid length of last-formed latewood through successive growth rings from the pith. Results from two different trees are included in the figure to show that in one tree the tracheids are shorter throughout the range of growth rings compared with that of the other (from Wardrop, 1948).**

The other source of variability in tracheid length of radiata pine is the variability between contrasting growing sites (Harris, 1965; Cown, 1974; Cown and Kibblewhite, 1980). Harris (1965) reported that tracheid length in radiata pine varies country wide in a similar manner to that for wood density (see next section) i.e. a gradual decrease from the North to South of New Zealand. Cown and Kibblewhite (1980), although agreeing with Harris, reported that the magnitude of variations in tracheid length from the North to South of New Zealand is not as great as that observed for density. For example, at two growth ring levels (15th and 45th growth rings) they observed that tracheids differ in length by about 3.3 mm to 4.1 mm in the North (Auckland) to 2.6 mm to 3.6 mm in the South (Canterbury).

2.4 PHYSICAL PROPERTIES

2.4.1 Density

Density has long been considered the best single index of intrinsic wood quality. The well established relationships between density and clearwood properties are listed in Table 4.8 of the USDA Wood Handbook (1987). The relationship can be described by the following equation:

$$S = K(D)^n \qquad (2.1)$$

where:

S = clearwood strength or stiffness property (MPa),

D = density (kg/cu.m),

K = a proportionality constant differing for each property, and

N = an exponent for each property which defines the shape of the curve.

2.4.1.1 Within-ring density variation

Walker (1993) emphasised the importance of within-ring variability in density. He stated that most species apart from Araucaria spp. and diffuse-porous hardwoods, show distinct differences in wood density across the growth ring. This is primarily a response to seasonal climatic variations and the formation of latewood. The density variation across a growth ring far exceeds the density variation between trees.

Harris (1969) reported that radiata pine shows a relatively mild contrast between earlywood and latewood density with any one annual growth layer, but the density gradient between corewood and outerwood has the effect of extending the total range of density across the stem. The variation in density of radiata pine is compared with that found with spruce, loblolly pine and Douglas fir (Harris, 1973; 1981). The maximum density range within the annual growth layer in radiata pine is usually about 1.8:1 which is not much more than spruce, but less than loblolly pine for which the maximum density range is about 2.3:1 and much less than Douglas fir with extremely contrasted earlywood and latewood, where the latewood to earlywood density ratio approaches 5:1.

2.4.1.2 **Between-ring density variation**

The variation in density from pith to bark is a significant feature in radiata pine and this is the major source of variation in the species (Cown, 1974; Harris, 1981). Wood density increases by 30 to 40 percent over the first 20 to 30 annual growth layers from the pith (Harris, 1981; Cown *et al.*, 1991a). For example, Cown and McConchie (1980) examined wood density variations in a stand of radiata pine in Kaingaroa Forest, New Zealand. Discs were taken from 10 trees starting from the butt of each tree and at intervals up the stem representing 5 years apical growth (5 rings). The discs were used for analysis of wood property variations including density. They found a typical pattern in which density increases from the centre of the stem outwards in all cases (Figure 2.7). At breast height the increase was from 386 kg/cu.m to 480 kg/cu.m.

The nature of corewood in radiata pine (Cown, 1974, 1980; Cown and McConchie, 1980; Harris, 1965) is summarised by Walker (1993). Cown (1992a) reported that corewood can account 50 percent of the stem wood of a 30-year-old well thinned fast-grown radiata pine (Figure 2.8). Comparing radiata pine with Douglas fir, it is clear that for radiata pine the effects of corewood are more closely confined to the zone immediately adjacent to the pith (first 7 - 12 years) even when grown on a shorter rotation than that for Douglas fir. In the latter case the corewood zone is prolonged (first 20 - 30 years). Recently Cown (1992a) has advocated the equally arbitrary definition for corewood of radiata pine as that part of the stem adjacent to the pith having a basic density below 400 kg/cu.m. This pragmatic approach passes over the acknowledged experience that not all properties (density, microfibril angle, stiffness, mechanical properties etc.) move from corewood to outerwood at the same point of time, and would specifically disadvantage the stands in higher latitudes and elevations.

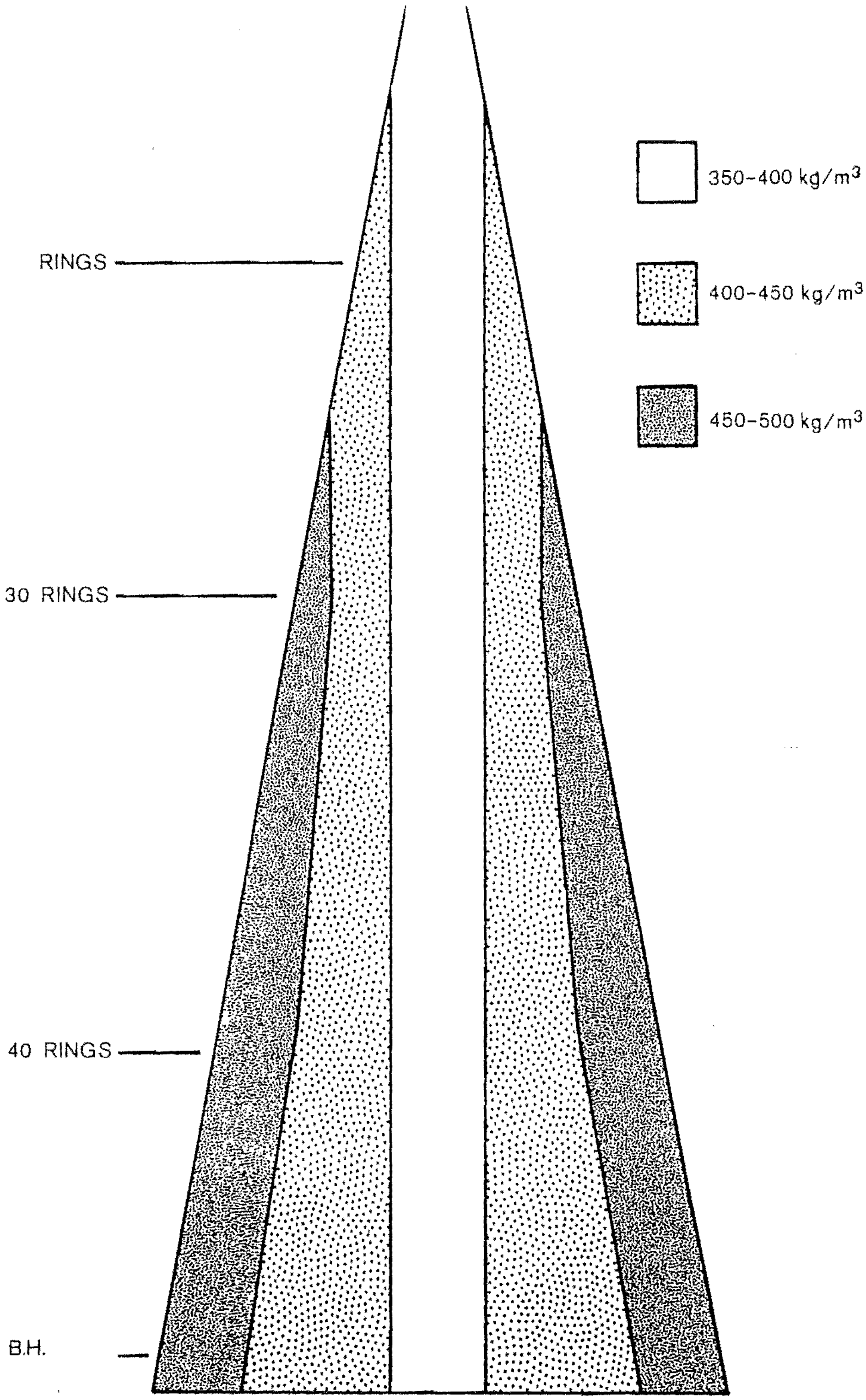


FIG. 5—Within-tree density distribution.

Figure 2.7 **Within-tree density distribution (from Cown and McConchie, 1980).**

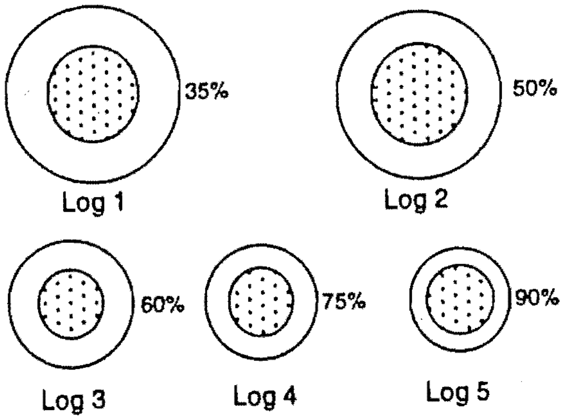


Figure 2.8 **Corewood incidence by log height classes in a 25-year-old crop, assuming the 'first-10-rings' definition (from Cown, 1992a).**

2.4.1.3 **Variation up the stem in density**

The effect of height up the stem on density was reported subsequently. Cown and McConchie (1983) in their study of basic density on samples collected from 10 trees of 12-year-old radiata pine from Kaingaroa Forest observed a drop in the mean density of 20 kg/cu.m between the butt and 3-metre height up the stem followed by a decrease of about 10 kg/cu.m for each further 3-metre height increment to the apex. Later in other studies of density on samples collected from 10 trees of 24-year-old and 10 trees of 34-year-old radiata pine Cown and McConchie (1983, 1984) observed a decrease in the mean basic density of 20 - 30 kg/cu.m for each 10-metre height to the apex. Cown *et al.* (1991a) reported that the average difference in basic density between the butt logs and top logs of radiata pine ranges from 7 to 11 percent. Cown (1992b) presented a systematic diagram (Figure 2.9) for basic density variation from the base of the tree to the top. It can be seen from Figure 2.9 that for trees of all ages basic density decreases from the base of the tree to the top.

Concerning the low density corewood in the stem, Walker (1993) reports that there is little difference in quality between the corewood in the top-most part of the tree and the corewood in the butt log which had been formed years earlier when the green crown of the younger tree was much lower (Figure 2.10). However, the corewood zone which can be described as a cylinder extending the length of the tree, predominates in the top log and is proportionately less significant in volume terms in the lower logs.

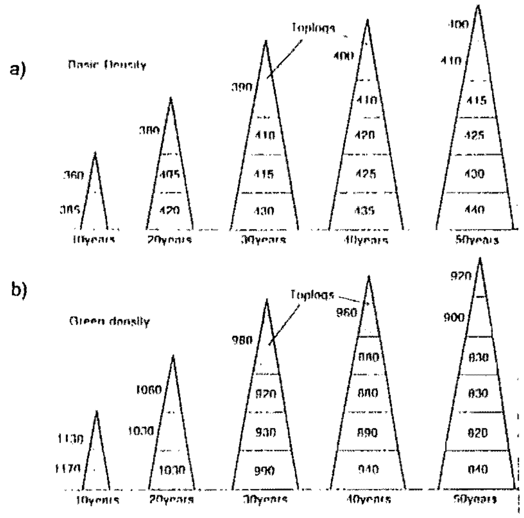


Figure 2.9 **Variations of basic density** (a) **and green density** (b) **from the base of the tree to the top (from Cown, 1992b).**

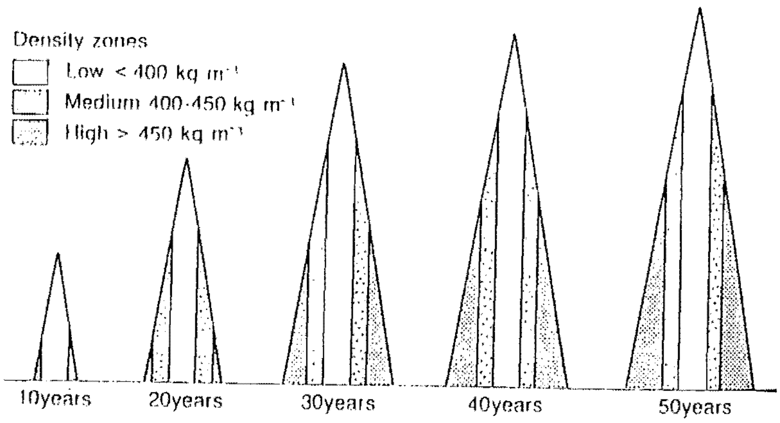


Figure 2.10 **Basic density in the tops of older trees is very similar to that of 10-year-old trees of radiata pine (from Cown, 1980).**

2.4.1.4 **Between-tree density variation**

Concerning between-tree variations in radiata pine, the range of wood density encountered in trees of the same age and crown class growing in an apparently uniform environment is very wide. For example, corewood values ranging from 270 to 360 kg/cu.m. were recorded in 6-year-old trees by Harris (1966) and in the mature outer wood of 35-year-old trees the highest values were frequently 50 percent greater than the lower values on any one site (Harris, 1965). Cown and McConchie (1983) examined the within-stand variation of basic density using increment cores taken from a typical 24-year-old stand of P.radiata grown in Kaingaroa Forest, Central North Island. They reported that for a comparable sample (same age and same site) a between-tree variation in average cross-sectional basic density of 15 kg/cu.m to 25 kg/cu.m can be expected (Figure 2.11).

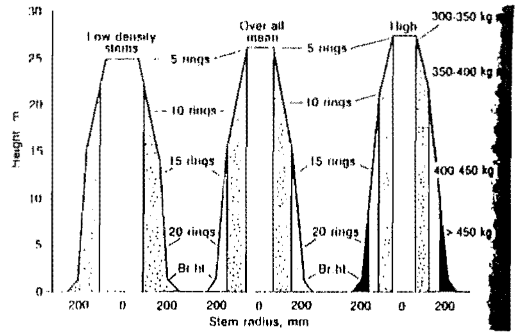


Figure 2.11 **Between-tree variation of basic density in a typical 24-year-old stand of <u>P.radiata</u> (from Cown and McConchie, 1983).**

Concerning genetic breeding on the basis of density, Harris (1965) examined the within- and between-tree variations in density for three radiata pine trees growing in the same site from Kaingaroa Forest, New Zealand. He found that the first tree had a basic density of 350 kg/cu.m at the first growth layer increasing to 460 kg/cu.m at the 26th growth layer. The second tree started at 310 kg/cu.m and this increased to 360 kg/cu.m while the third tree started at 280 kg/cu.m and increased to 460 kg/cu.m at the respective growth layers. From these results he concluded that the first tree is most desirable because of its relatively high density in both outer wood and corewood. The second tree would be undesirable because of its consistently low density, and the third tree is also undesirable because of its low density corewood and steep gradient. From these he concluded that an initial high density in corewood was beneficial regardless of subsequent changes in density as in no instance did basic density decrease with distance from the pith (Figure 2.12).

2.4.1.5 **Between-site density variation**

The other important source of variability in radiata pine is the variability between contrasting growing sites. Walker (1993) reported that the natural populations of <u>P.radiata</u> are restricted to three mainland areas in California and two islands off the Coast of Mexico, comprising an area of less than 700 ha. Despite the relatively restricted areas, these populations range from 30^{o} N to 40^{o} N and have proved to be of sufficient diversity for successful breeding of improved forms (Bannister, 1973; Burdon and Bannister, 1973).

The environment exerts strong control over the average basic density of trees in a stand. A trend which is frequently observed is that of lower basic density with higher altitudes of the site and increasing latitude (Walker, 1993).

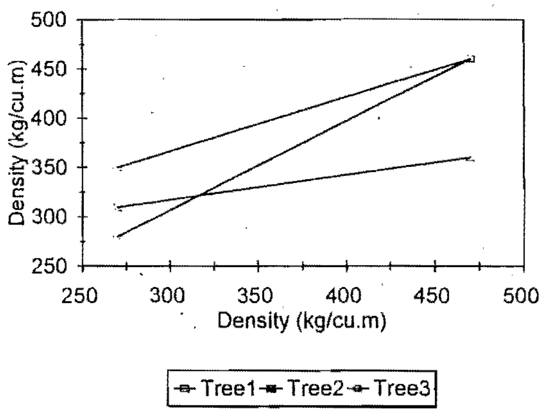


Figure 2.12 **Schematic representation of Harris' three types of density trends in radiata pine.**

Cown (1974) has made an extensive survey of radiata pine throughout New Zealand. His findings show that the wood density tends to decrease with increasing latitude and altitude: the decrease in outer wood density amounts to about 10 kg/cu. m. per 1 degree increase in altitude or per 1000 metre increase in latitude (Figure 2.13).

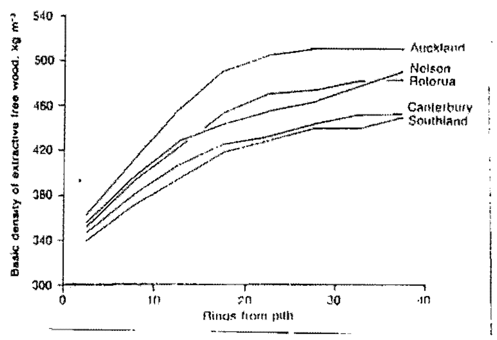


Figure 2.13 **Wood density map of New Zealand radiata pine plantation forest (from Cown, 1974).**

2.4.2 **Spiral grain**

Spiral grain is fundamentally a simple concept in which the wood grain, for example, as seen on the outside of a log, moves round in a spiral rather than parallel to the longitudinal axis of the log (Harris, 1989). Harris observed that so many technical containing spiral grain, that some wood scientists have taken the view that this is the most serious single defect in various plantation-grown softwoods.

The presence of spiral grain has significant practical implications: strength is lowered, while the degree of twist on drying and the amount of pick-up on machining increases as the degree of spirality of the grain increases (Dinwoodie, 1981).

The consequences of spiral grain are frequently encountered in the form of twist in dry sawn timber, distortion in plywood sheets, short grained failure of timber under stress and problems during machining (Harris, 1978). Bendtsen (1978) reports that the instability associated with spiral grain, coupled with the abnormal longitudinal shrinkage of corewood and excessive amount of compression wood are responsible for the poor reputation of solid wood products from rapid-grown plantation timber.

The effects of deviations in grain angle from the axis of sawn timber are well illustrated by Harris (1989). A grain angle of five degrees will cause 10 percent reduction in tensile strength, whereas the grain angle can be as high as ten degrees before there is an equivalent loss in compressive strength parallel to the grain, and the effect on bending lies between the two extremes as shown in Figure 2.14.

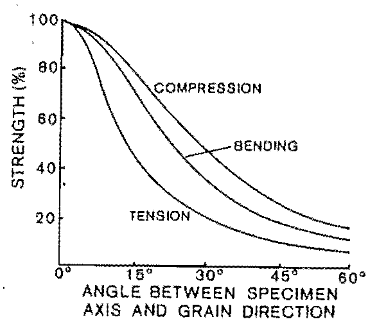


Figure 2.14 **Effect of grain angle on strength properties (from Harris, 1989).**

Strength as a function of the grain angle can be estimated using the empirical Hankinson equation as follows:

$$S = (P.Q)/(P.\mathrm{Sin}^N\theta + Q.\mathrm{Cos}^N\theta) \quad \text{..........} (2.2)$$

Where: S = strength of wood in which the grain angle is inclined at an angle θ degree to the direction of the load;

P = strength parallel to the grain (θ = 0 degree);

Q = strength perpendicular to the grain (θ = 90 degree); and

N = a constant for the particular strength property.

The values of n and associated ratios of Q/P are given in the USDA Wood Handbook (USDA, 1987, p. 4-29) as follows:

Property	Values of N	Values of Q/P
Tensile strength	1.5 - 2.0	0.04 - 0.07
Compressive strength	2.0 - 2.5	0.03 - 0.4
Bending strength	1.5 - 2.0	0.04 - 0.1
Modulus of elasticity	2.0	0.04 - 0.12
Toughness	1.5 - 2.0.	0.06 - 0.1

Lavers (1967) in his analysis of the strength properties of timbers reported that in conifers the first formed rings typically have little spiral grain; a left hand spiral then develops reaching a maximum at about 10 years of age. Then follows a rapid decrease in spirality to a straight grain condition and finally a gradual development of right hand spirality with senescence. This view was supported by Harris (1989).

Langlands (1938) examined spiral grain in clearwood (20x20 mm) specimens on 22-, 23-, 33- and 52-year-old plantation grown radiata pine trees in Australia. He reported that all his trees contained spiral grain near the pith, but in every case the slope of grain decreased with increasing distance from pith (in general from more than 1 in 10 to less than 1 in 20), showing that this defect is much less prominent in the outerwood of older trees.

Concerning grain deviation in radiata pine, Harris (1978) reports that spiral grain is the most common defect in the corewood. He suggested that spiral grain has been neglected by the timber industry in New Zealand for the following reasons:

1. Spiral grain is confined to corewood which in turn is guarded against by the grading rules;

2. Spiral grain in radiata pine seldom reaches extreme values, frequently lying within the range of 5 - 10 degrees;

3. The climate over most of New Zealand is maritime in nature, so that dry timber shipped from one place to another would not normally encounter violent differences in equilibrium moisture content.

A recent re-evaluation by Cown *et al.* (1991b) argues that spiral grain in radiata pine is much more significant than had been previously appreciated (Harris, 1978, 1989). The principal point to note is that extensive data from fifty 25-year-old trees (Figure 2.15) show that grain angles in excess of 5 degrees are frequently maintained within the first 10 growth rings from the pith, and the drop off is more gradual than previously suggested (Harris, 1978), that the 'zero angle' situation does not occur until about 15 rings from the pith. Detailed analysis of the same data (Cown *et al.*, 1991b) showed that a 5 degree of grain deviation is the critical point, above which twist sufficient to down-grade the timber according to the New Zealand Timber Grading Rules - NZS3631:1990 is very likely to occur, even with appropriate restraint during drying.

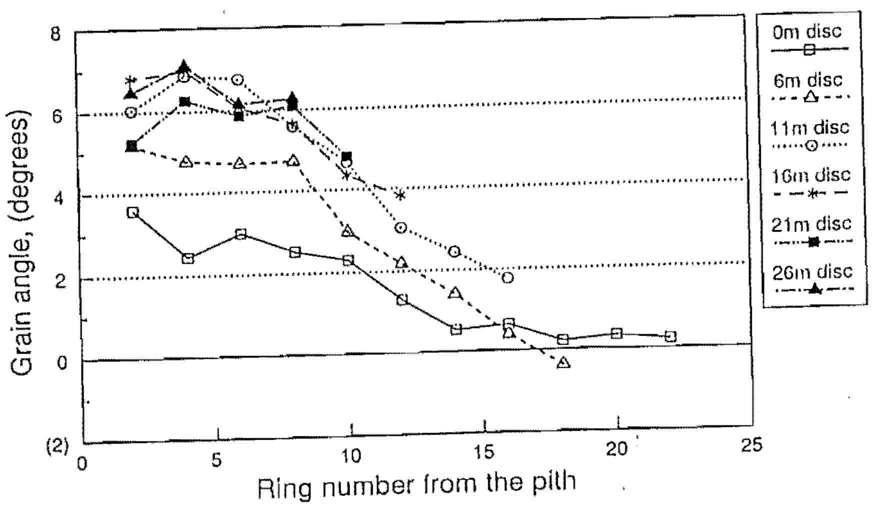


Figure 2.15 **Within-tree variation of mean grain angle for 25-year-old radiata pine trees (from Cown *et al.*, 1991b).**

2.5 MECHANICAL PROPERTIES

2.5.1 Within-ring variations

Kloot (1952) examined tensile strength and air-dry density on 0.08 mm thick micro-specimens taken from radiata pine. He reported that the pattern of air-dry density variations within and between growth rings exhibits much the same characteristic as the tensile strength patterns. The patterns for strength and specimen weight in his results for a sample of radiata pine across approximately seven growth layers are shown in Figure 2.16 The figure shows clearly that there is a correlation in the cyclic variation of tensile strength and density within the growth ring. The degree of overall correlation between the two properties, however, was relatively low with a correlation coefficient (r) value of only 0.64. From this he concluded that as several factors may affect the apparent density of specimens without contributing to strength, he considered that density variation could not be effectively used for a detailed study of strength variation.

2.5.2 Between-ring variations

Langlands (1938) examined mechanical properties on clearwood (20x20x300 mm) specimens from 22-, 23-, 33- and 52-year-old plantation grown radiata pine trees in Australia. He reported that in the case of young trees (22- and 23-year-old) there was a steady increase in density, modulus of elasticity and bending strength with increasing distance from pith, indicating that if they had been cut later in life the outer portions would have been denser, stiffer and stronger than the wood actually tested. The 33-year-old trees showed the same tendency of increasing density and strength but with these properties beginning to flatten out near the cambium, indicating that at the time of felling the trees were laying wood which was approaching maximum

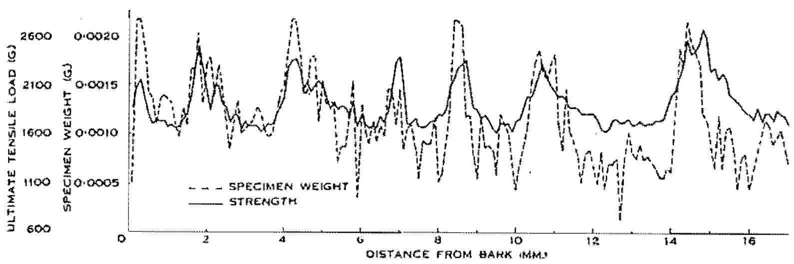


Figure 2.16 **Micro-tensile strength and density patterns for a sample of air-dry radiata pine (from Kloot, 1952).**

density and strength. In the case of 52-year-old trees there was little change in density with distance from pith after the 30th growth ring.

Kloot (1957) examined the radial variation of bending strength on standard size clear specimens of wood taken from 40-year-old radiata pine in Australia. He reported that in the early years of growth when the tree was young the strength of timber was 41.4 MPa in bending. This increased with age, reaching a maximum of 124.1 MPa at the age of 32.

Walford (1985) examined the relationship of cambial age with modulus of elasticity, modulus of rupture and maximum crushing strength, using small clear specimens of radiata pine from throughout New Zealand. He observed a similar increase in all mechanical properties with increasing cambial age.

Concerning the effect of core-to-mature wood variation in radiata pine, a comparison of the results from in-grade testing by Walford (1982) of a 40-year-old radiata pine and bending strength tests by Bier and Collins (1985) of a 28-year-old radiata pine showed a marked difference in that the former was 14 percent higher in bending strength than the latter. The effect of age on mechanical properties of radiata pine timber grown in New Zealand is shown in Figure 2.17.

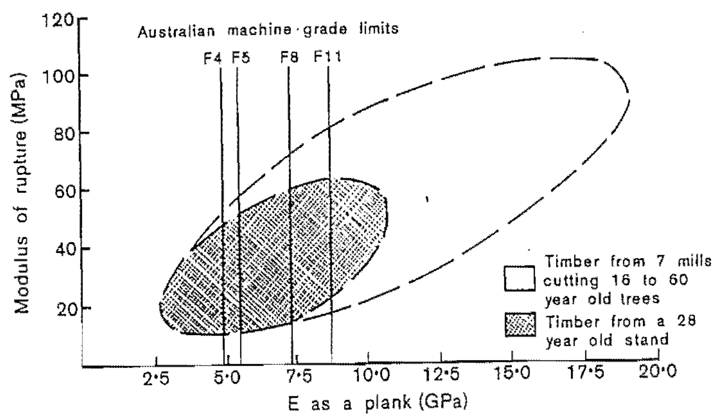


Figure 2.17 **Comparison of old and new crop mechanical properties (from Bier, 1985).**

2.5.3 **Variations up the stem**

Vertical variations on mechanical properties in radiata pine were reported by Langlands (1938). He examined specific gravity, bending strength, compression strength and hardness on 20x20 mm clearwood samples sawn from a 22-, 23-, 33- and 52-year-old radiata pine trees. For his specimens taken from the 33-year-old radiata pine trees, he divided the height of the tree into five 2.4 m sections and made a comparative analysis of changes in bending and compression strength up the height of the tree. His results showed that bending strength was reduced by 2 - 5% in moving from the 2.4 m section to the 4.8 m section, by 5% in moving from the 2.4 m to the 7.2 m section, and by 10% in moving from the 2.4 m section to the 9.6 m section up the height of the tree. For compression strength he observed a much higher overall reduction of 19 - 22% up the tree.

2.5.4 **Between-tree variations**

Concerning the between-tree variations, Kloot (1952) compared the tensile strength and compression parallel to the grain properties on 0.08 mm thick specimens cut from two 15-year-old radiata pine trees grown on the same site in Australia. One of these trees was fast grown while the other was slow grown (i.e. because of suppression). He observed that for wood taken from the slow grown tree, the value of tensile strength was 1.4 times that for the fast grown tree. He also observed a ratio of 1.4 for compression strength, except that in this case the specimens were tested in the green condition. He stated that this strength variation between the two groups of trees was due to rate of growth.

2.6 **OTHER SPECIES**

2.6.1 **Microfibril angle**

The general trends are similar to those observed in radiata pine (Dadswell and Wardrop, 1959). Hiller (1964) reported that the microfibril angle of the S_2 layer in latewood tracheids of slash pine (P. elliottii) and loblolly pine (P. taeda) is less than those in earlywood tracheids. Average latewood microfibril angle in loblolly pine decreases as distance from pith increases at any height level and increases in the same year's radial growth with increasing height up the stem (Pillow, *et al.*, 1959).

Hong and Wang (1988) studied variations in microfibril angle on earlywood and latewood samples cut from Taiwan red cypress (Chamaecyparis formosensis) grown in plantation and natural forests. Samples were taken at various heights above ground. They reported that the microfibril angles were consistently larger in earlywood than latewood. In plantation grown trees, for example, the change in microfibril angle from the pith to the cambium was from 30 degrees to 18 degrees for earlywood while it was only from 20 degrees to 10 degrees for latewood. They also observed that the microfibril angle up and across the diameter of the stem is different from earlywood to latewood. For instance, the earlywood microfibril angle decreased from 30 degrees near the pith to 15 degrees near the cambium at the base of the tree and from 30 degrees to 14 degrees at 1.3 m height near the cambium while the latewood microfibril angle decreased from 20 degrees near the pith to 8 degrees near the cambium, and from 20 degrees at the base to 6 degrees at 1.3 m height near the cambium.

Wu and Wang (1988) in their study of wood properties of A. magnum and A. auriciliforms, reported that microfibril angle decreased from 25 degrees near the pith to 5 degrees near the cambium.

In contrast earlywood microfibril angle in Western hemlock remains high during the first twenty years of growth and then gradually increases while microfibril angle in the latewood decreases steadily as the tree grows older (Wellwood and Smith, 1962).

2.6.2 **Mechanical properties**

Kloot (1952) examined tensile strength and density on 0.08 mm thick micro-specimens taken from a number of species including Douglas fir (Pseudotsuga taxifolia), woolly butt (Eucalyptus lengifolia), wattle (Acacia deabata), mountain ash (E.regnans), alpine ash (E.gigantea), coach wood (Ceratopetalium apetalum), and messmate stingy bark (E.obliqua). He observed a clear difference between earlywood and latewood. As shown in Figure 2.18 tensile strength falls from a high value at the edge of the latewood band to a low value at the beginning of the earlywood band of the next growth ring. He also observed that in general earlywood specimens fail by rupture of the cell walls, but the latewood specimens fail in the middle lamella.

Manwiller (1972) measured tensile strength and stiffness on 0.03 mm thick specimens cut from 72 spruce (Abies picea) trees. For his earlywoood specimens, he obtained values of 3.5 GPa and 5.5 MPa for modulus of elasticity and tensile strength respectively. The respective values for the latewood specimens were 7.6 GPa and 13.1 MPa.

Bendtsen and Senft (1986) examined bending strength, compression strength parallel to the grain, specific gravity, tracheid length, microfibril angle and reaction wood on microtest specimens of 30-year-old plantation grown cottonwood (Populus deltoides) and loblolly pine (Pinus taeda) in the USA. Their results showed that all properties are at a minimum in the earliest annual rings, with a marked increment for a number of years, and then exhibit stability or only a gradual increment thereafter. For example, they observed about a fivefold increase in the average modulus of elasticity (2.1 GPa to 11.0 GPa) and about a threefold increase in the average modulus of rupture (27.6 MPa to 82.7 MPa) from rings adjacent to the pith to those near the cambium in loblolly pine. They also reported that there is a marked improvement for other properties in moving from pith outwards in both species. They observed the following ratios for latest outerwood to first formed juvenile wood in loblolly pine: compression strength parallel to the grain 2.4:1 and cell length 2.7:1. Microfibril angle decreased from 36.5 degrees for early juvenile to 12.3 degrees for late mature wood (i.e. 3.0:1 ratio).

Concerning the change in specific gravity, Bendtsen and Senft (1986) reported that the change with age was quite modest, amounting to only about 10 percent increase from rings adjacent to the pith to those near the cambium in cottonwood and about 40 percent in loblolly pine. From this they concluded that these increases were not sufficient to account for the increases observed in mechanical properties for either species. They concluded that the large change in mechanical properties with age apparently reflected the composite effect of increasing specific gravity, cell length, and microfibril angle.

To test the above deduction Bendtsen and Senft used a multiple regression analysis and showed that specific gravity, cell length and microfibril angle contribute about equally to the improvement of all mechanical properties. For example, with their one-variable model in pine, the values for the coefficient of determination, R-square between specific gravity and mechanical properties ranged from 0.42 to 0.64; for cell length from 0.56 to 0.62, and for microfibril angle from 0.44 to 0.50. In a two-variable model the value of R-square was improved to more than 0.80, which means that in combination (i.e. specific gravity + cell length or specific gravity + microfibril angle or cell length + microfibril angle) these variables explain 80 percent of the improvement in stiffness, bending strength and compression strength values. For all mechanical properties, either specific gravity or cell length combined with microfibril angle gave the best two-variable model for pine while for cottonwood specific gravity was always included in the best two-variable model.

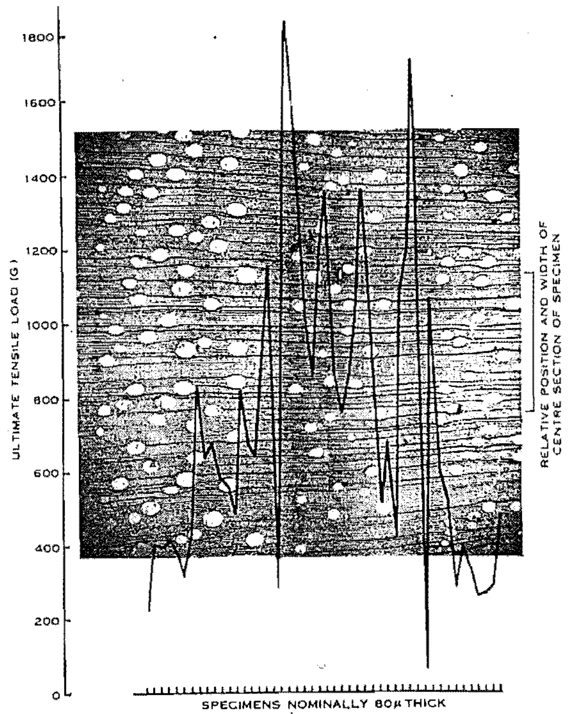


Figure 2.18 **Variations of tensile strength within a growth ring of mountain ash.**

Boone and Chundof (1972) studying the properties of young plantation grown Caribbean pine (Pinus caribaea) from Puerto Rica showed that clearwood plantation material had less than 50 percent of the specific gravity, bending strength and stiffness of published values (which probably related mainly to mature wood taken from the natural forest which contained much mature/over-mature timber).

In the United States McAlister and Clark (1991) examined the effect of juvenile wood on bending strength of loblolly pine (P.taeda) from three plantation sites established under the "South-wide pine seed source" study. For all three sites they found that juvenile wood had a lower value than mature wood. For example, for samples taken from the Atlantic Coastal Plains, they found a specific gravity of 0.41 for juvenile wood while the value for mature wood was 0.57. The respective values of the modulus of elasticity for juvenile wood and mature wood were 5.4 GPa and 12.5 GPa, and for the modulus of rupture the values for juvenile wood and mature wood were 37.9 MPa and 69.9 MPa respectively.

Kretschman and Bendtsen (1992) examined tensile strength and stiffness on 38x89 mm boards cut from 28-year-old plantation grown loblolly pine (P.taeda) trees in North Carolina, USA. Before testing they graded the boards into three select structural grades (SS) as No.1, No.2 and No.3. Their results showed that the proportion of higher grades decreased as the amount of juvenile wood in the cross-section increased. The same trend was also true for mechanical properties, as the proportion of juvenile wood increased the values of tensile strength and modulus of elasticity decreased. For example, for No.3 select structural grade, as the proportion of juvenile wood increased from 0 to 100 percent in the sample population, the modulus of elasticity decreased by 37 percent while tensile strength decreased by 43 percent.

The effect of the position of the timber up the stem on mechanical properties was studied by Austin (1988). He examined specific gravity and mechanical properties in dimension lumber cut during normal mill production from 20- and 50-year-old slash pine (P. elliottii) in the USA. Comparing material cut from butt logs and top logs, for the 20-year-old trees the butt logs were 7%, 51% and 8% higher in specific gravity, modulus of rupture and modulus of elasticity respectively while the respective values for the 50-year-old trees were 15%, 56% and 36% higher. Note the divergence between strength and stiffness values on ascending the stem.

McAlister and Clark (1991) examined the effect of geographic location on the bending properties of clearwood specimens cut from juvenile wood and mature wood of loblolly pine (P.taeda) in the USA. Specimens were collected from three geographic locations (Dooly Country, Spadling Country and Clark Country). They reported that geographic location was a significant factor in specific gravity, modulus of elasticity and bending strength for both juvenile wood and mature wood. For example, for both juvenile wood and mature wood one of the geographic locations (i.e. Dooly Country) was 50 to 80 percent higher in stiffness and 15 to 20 percent higher in bending strength compared to the respective values for the wood from the other two geographic locations.

2.7 COMPRESSION WOOD IN SOFTWOODS

Dinwoodie (1981), and Timell (1986) report that reaction wood is an important defect with regard to utilization of timber. When trees are inclined to the vertical axis, usually as a result of wind action or growing on sloping ground, the distribution of growth promoting hormones is disturbed, resulting in the formation of this atypical type of tissue. In softwoods, this tissue (compression wood) grows on the lower side of the trunk and is characterised by having higher than normal lignin content, larger microfibril angle in the S_2 layer - resulting in increased longitudinal shrinkage and lower transverse shrinkage, greater brittleness than normal wood and generally darker in appearance. Compression wood has higher than normal density, and displays up to ten times greater than normal longitudinal shrinkage, reduced permeability and strength (Senft *et al.*, 1985).

According to Timell (1986), many of the properties of compression wood are extremely undesirable in both pulp wood and lumber. Mechanical pulp cannot be made from compression wood and chemical pulps prepared by sulphite method have poor strength properties. For kraft pulps, however, the presence of compression wood is less serious. In lumber, hard dense compression wood is difficult to work and nail. When lumber contains both normal and compression wood, the high longitudinal shrinkage of compression wood causes severe warping, distortion and cross checking, and this is the most serious problem in the utilization of such sawn timber.

Timell (1986) reports that compression woood is very common and probably more wide spread than is generally appreciated. There is no forest or plantation tree that does not have at least some compression wood in its stem, and branches always contain substantial amounts. Concerning radiata pine, he wrote that when exposed to the prevailing wind, P. radiata tends to form compression wood, and every stem of this pine probably shows the harmful effects of wind. According to Harris (1977) logs from almost any forest in New Zealand frequently contain up to 20 percent by volume of compression wood. Cown and Kibblewhite (1980) state that little is known about the incidence of compression wood in radiata pine in New Zealand. It is estimated that old, untended stands contained 10 to 15 percent by volume of compression wood, largely in association with stem malformation.

In the case of compression wood in New Zealand grown radiata pine, Cown and McConchie (1981) report that much of the compression wood is of the mild type with little or no impact on the utilization of the wood: that is probably the main reason why compression wood has not been received much attention in New Zealand.

Concerning compression wood classification, Burdon (1975) developed a useful practical method during his study of compression wood in 18 clones of 12-year-old radiata pine trees from four different sites (Gilenbervie, Whaka, Gwavas and Berwick) in New Zealand. He classified the opaque and reddish compression wood observed in thin microtome sections into 6 different grades of severity, from 0 to 5, namely normal wood (0), latewood patchily opaque (1), latewood generally opaque (2), latewood opaque and earlywood partly opaque (3), latewood and earlywood generally opaque (4), and latewood and earlywood highly opaque (5). He considered grades 1 and 2 as mild and grades 3 - 5 as severe compression wood.

On the basis of the above classification Burdon marked boundaries and grades of compression wood on his disc specimens. A glass plate was placed over the disc, and disc circumference and boundaries and grades of compression wood were traced on a gauged, translucent paper. Each zone was excised, and its area was measured by weighing. A compression wood rating was defined as:

$$(A_1 \times G)/(A_2) \qquad (2.3)$$

Where: A_1 = cross-sectional area of the zone of compression wood;

G = compression wood grade of that zone, and

A_2 = the area of the disc.

Using Equation (3), Burdon (1975) calculated the percentages of both severe compression wood and total compression wood for his four sites. He observed that severe compression wood ranged from only 6 percent to 23 percent in all the four sites, while the range for total compression wood was from 34 percent to 44 percent.

Harris (1977) examined tracheid length on specimens taken from 8-year-old radiata pine selected from Kaigaroa Forest, New Zealand. First he separated compression wood from normal wood. His results showed that earlywood and latewood tracheid length values differ in compression wood compared to normal wood. For example, for compression wood samples taken from a number of growth layers ranging from 4 to 15 from pith, tracheid length varied from 1.9 mm to 2.5 mm for earlywood and from 2.1 mm to 2.6 mm for latewood. For samples from opposite wood taken from the same number of growth layers, tracheid length increased from 1.9 mm to 3.2 mm for earlywood and from 2.1 mm to 3.3 mm for latewood.

Concerning the association of compression wood with corewood, Timell (1986, Volume 2, p.77) states:

> "There is no stem region where compression wood is found more frequently than the first few growth rings at the centre near the pith. The reason for this is obvious. Young trees are lithe and easily bent, for example under the influence of wind or snow. At the same time, however, a young stem is strongly gravitropic and usually able to right itself quickly with the aid of appropriately located compression wood. As a result regions of compression wood are often observed surrounding the pith long after the trunk has resumed a vertical position".

Zobel *et al.* (1972) and Zobel and Blair (1976) reported that compression wood is found interspersed in corewood of softwoods, particularly in rapid growth material. Dutoit (1963) noted that the most obvious cause of warping in lumber that contains corewood is the relatively large amount of compression wood associated with corewood and the large microfibril angle common to wood laid down in the early stages of growth.

Haght (1958) reported that the proportion (percent by volume) of compression wood in the corewood of loblloly pine (P. taeda) was 42 percent compared to only 7 percent in mature wood. Pearson and Gilmore (1971) also reported 61 percent of compression wood for the same species. Bendtsen and Senft (1986) examined reaction wood in loblolly pine. They reported that the percentage of compression wood fibres averaged 35 percent in the early years of growth and showed a slight decreasing trend with age.

2.8 **TESTING OF WOOD FOR MECHANICAL PROPERTIES**

The mechanical and related properties of timber have been studied on specimens of various shape and size. A principal separation is made between timber or lumber of commercial sizes and containing a variety of natural defects - knots etc. and small clear wood specimens which by definition are free of obvious defects. In the current study both clear wood (both micro-specimens and standard test sizes) and defect containing (full-size) members are employed. Hence it will be necessary to review the importance and background of each.

2.8.1 **Tests on micro-specimens**

In the Oxford Dictionary (Brown, 1993) 'micro' is defined in terms of instruments, techniques and disciplines dealing with small effects, quantities, containing or pertaining to something in minute form, or degree or in a reduced size. Hence micro-specimens in wood means samples of minute size.

There is no standard size for micro-specimens of wood. Specimen size varies according to the purpose of a particular study. These generally relate to either fundamental properties of wood at the fibre level or to differentiate between properties of earlywood and latewood. For example, Wardrop (1951) used single

Bendtsen and Senft (1986) examined bending strength, compression parallel to the grain, specific gravity, fibre length, microfibril angle and reaction wood on micro-specimens of 0.03 mm and 3.125 mm thick, cut from cottonwood species and loblolly pine. For bending strength they used 56.25 mm long by 3.13 mm thick specimens, for compression parallel to the grain they used 31.25 mm long by 3.13 mm thick specimens and for fibre length and microfibril angle measurements they used 0.03 mm thick specimens.

2.8.2 **Tests on standard size specimens**

Two schemes for testing small clear specimens of timber are employed internationally (Armstrong, 1955). One using a test piece 2 inches square in cross-section, originated in the USA as long ago as 1891 and was later adopted by the Forest Products Laboratory, Maidson, Wisconsin. This standard has been accepted as the general plan of testing in many countries. The second scheme utilizes a smaller test piece, 2-centimetre square in cross-section which originated in Europe and is called the 'Monin' system. This standard is used in many continental countries and also New Zealand and Australia.

Since 1949 the 2-centimetre system has been used in the U.K. because the smaller specimen size is more suitable for the systematic sampling of small second-growth trees and for the preparation of matched groups of test specimens for comparative purposes (Armstrong, 1960).

The sampling of the material for testing and the testing procedures of small clear specimens follow recognized international procedures. For the 2-inch size the procedures are laid down in the American Standard, American Society for Testing Materials (ASTM D:143-52). The British standard (BS 373:1957), 'Methods of testing small clear specimens of timber' describes the procedures for both the 2-inch and 2-centimetre standards.

The estimated average strength values from the standard size clear wood specimens enable comparisons between species and provide basic technical data for efficient utilization. Sunley (1965) stressed that the average strength values were not working stresses for use in design, but were the basic data used for the derivation of the working stresses which were published in design specifications and building codes.

The historic connections between clear wood samples and natural timber are described by Sunley (1965) and these are summarised below. However, more recent thinking (see next section) prefers to determine working stresses of timber for actual graded packets of timber. The earlier methodology went as follows:

1. The basic stress for each species and strength property was obtained by dividing the statistical minimum value by the safety factor for each property. The statistical minimum was obtained by subtracting 2.33 times the standard deviation from the mean of the property tested at the green condition (this corresponds to the lowest 1 percent value for the population sampled). A safety factor for bending strength, tensile strength and shear of 2.25, and for compression parallel to the grain, of 1.4 was applied (and provides for both long-term loading and a factor of safety).

2. The average values for modulus of elasticity (MOE) were usually taken as the basic values and were not reduced.

3. The strength ratio of an actual piece of graded timber was determined as the ratio of the strength remaining after making allowances for maximum effects for various defects (i.e. knots, slope of grain, wane, rate of growth, checks, shakes, splits and drying defects) permitted in that grade compared with the strength of the clear, defect-free wood. Thus strength ratios ranging from 40 to 75 percent were defined to provide grades to which timber could be allocated according to the presence of defects that were liable to reduce its strength depending on the effect of the particular defect.

4. Stress grading rules were formulated by fixing a suitable strength ratio and specifying limitations for all the defects. For example, in the U.K. four stress grades with approximate strength ratios of 40, 50, 65 and 75 percent, respectively were considered suitable. For the modulus of elasticity, a strength ratio of 100 percent was assumed for all grades.

5. Finally, working stresses for stress grades in bending with for example, a strength ratio of 0.7 were calculated using the following formulae:

$$WS = [(\bar{S}-2.33\varrho)/(2.25)]\times(0.7) \quad (2.4)$$

Where:

WS = working stress in bending (MPa);
$\bar{S}$ = mean bending strength (MPa) and
ϱ = standard deviation (MPa)

As used in design codes, the "working stress" is the safe stress that a piece of wood can be subjected to under expected long term loads.

2.8.3 **In-grade testing**

In-grade testing means testing of lumber as it is produced at the sawmill (Madsen, 1975). The in-grade testing philosophy was developed at the University of British Colombia starting in 1972 (Madsen, 1984). The driving force behind this development was the National Building Code of Canada (NBCC) announcing that all structural material codes should be converted from the Working Stress Design (WSD) to the Limit States Design (LSD) format.

It was recognised that timber design under the LSD system could be placed in a position of considerable disadvantage if strength properties used were derived from small clear specimens. So more relevant information had to be developed.

Madsen (1978) reported that tests based on small clear specimens do not meet all of the following requirements for the in-grade testing philosophy, which required that:

1. The data should be suitable for both LSD and WSD.

2. The method should be practical and economical.

3. All the common strength properties for timber should be included.

4. The test specimens should be full size and representative of the sources from which structural grades of timber were developed.

5. The test specimens should be representative of structural grades.

6. The test methods should be suitable for handling large sample sizes.

Arising from the above listed in-grade testing principles, 100,000 timber specimens were tested in Canada (Madsen, 1978). These tests confirmed that the structural behaviour of timber is very different from that previously assumed. It was observed that the then current grading rules based upon the "strength ratio" concept performed poorly.

Madsen (1984) gave a detailed description of the importance of lumber testing from structural point of view. He stated that "timber" and "wood" should be treated as two different materials since their failure modes are totally different. Clear wood is stronger in tension than it is in compression. Therefore, when it is subjected to bending the initiation of failure is by the formation of wrinkles in the compression zone. This results in a somewhat ductile behaviour immediately preceding failure. Timber on the other hand contains growth characteristics such as knots. Such localised grain disturbances result in tensile stresses perpendicular to the grain, leading to a brittle fracture mode at a stress level lower than the compressive failure strength.

It should be obvious that we cannot obtain strength values from clear wood specimens and use them as a basis for timber use and design where the failure modes governing the behaviour of the two are so different. Nevertheless this was done in the past and that procedure had been the basis for traditional timber design codes. The choice of small clear specimen approach in the past was not without its reasons. For example, the structural timber used at that time was of a much better quality containing only a few knots so failure in the compression zone was favoured rather than brittle fracture failure (in tension). The second factor was that establishing the strength of timber using full size specimens was, and still is, a colossal undertaking because of the many combinations of species, sizes and grades involved.

Concerning statistical aspects, Madsen (1976) observes that commercially graded lumber as it is currently produced exhibits a great amount of variability in strength. In order to cope with this variability it is necessary to take mill samples containing at least 300 pieces. Smaller sample sizes would require a statistical treatment of the estimate of the lower 5-percentile values which would include a large "penalty factor" in order to make a confident statement. The magnitude of the "penalty factor" increases as the sample size diminishes. Since the calculation of the lower 5-percentile will affect very large quantities of lumber, even a small gain in the allowable stresses will easily justify the extra cost of testing, particularly if the test method is rapid. This observation is relevant to the experimental design of work reported in this thesis.

CHAPTER 3: **EXPERIMENTAL MATERIAL AND PROCEDURES**

3.1 **EXPERIMENTAL DESIGN**

The experiments reported here are described into two parts: the first experiment includes testing of full size (90x35 mm) graded timber in tension parallel to the grain and compression parallel to the grain; the second experiment includes testing of small clear (20x20 mm) specimens in bending and compression parallel to the grain. Material for the second experiment was selected subsequently from the material used in the first experiment.

A summary of the strength tests and the total number of test specimens in the two experiments is presented in Table 3.1.

Table 3.1 **Summary of tests and sample size in Experiments I and II: using graded lumber and small clear specimens.**

Experiment	Mode of testing	Number of samples	Total
I In-grade timber	Tension	915	1201
	Compression	286	
II Small clearwood specimens	Bending	2150	2564
	Compression	414	
Total		3765	3765

3.2 **RESEARCH MATERIAL FOR EXPERIMENT I: IN-GRADE TIMBER**

3.2.1 **Selection of material**

Forty eight trees from a 25-year-old plantation on the Canterbury Plains near Dunsandel in the South Island of New Zealand were felled and cross-cut into logs and discs as shown in Figure 3.1 a. The stem was cross-cut from the butt end to yield 3.6 m logs, progressing towards the top end. From the butt end, first a 50 mm thick disk (D1) was cross-cut followed by the first 3.6 m length log (L1). This operation continued until the final disk (D4) and log (L3) were cut from the whole tree, so that

4 discs of 50 mm thickness, 3 logs of 3.6 m length were obtained from each tree. In every case the small end diameter (sed) of the top logs was > 150 mm. In addition, a small log, 1.0 m long and less than 150 mm sed was cut from the remaining top portion of the tree. Internodal top logs from small trees were cut near D4 and for larger trees some metres above D4. This meant that a total of 192 discs (48x4), 144 logs (48x3) and 48 internodal top logs were available for study from the 48 trees.

As logs were cross-cut an identification number was attached to each at the centre of one end using a numbered tag of aluminium sheet 2.5x6.2 cm dimension. A similar number was given to each disc cut from the butt end of each log. The numbers were arranged to represent both the tree number (1 - 48) and the log number (B = butt log, M = middle log and T = top log). For the top internodal logs it was sufficient to indicate only the tree numbers.

After the cross-cutting operation was completed all the 144 logs were taken to Selwyn Sawmills Ltd, Hororata while all the 192 discs and 48 top internodal logs were brought to the School of Forestry and stored in a cold room.

3.2.2 **Saw milling**

At the sawmill the logs were sawn to the pattern shown in Figure 3.1b. This pattern gave a central cant and one, two or three 40 mm thick flitches on either side. The flitches were re-cut at the breast bench to yield timber of nominal dimensions 100x40 mm. In re-cutting the 100 mm wide cant, the objective was to box the pith within a single 100x40 mm piece and cut further pieces of the same size systematically working towards the cambium. In practice there was pith wander and the pith was rarely confined to a single board. Hence the number of pith containing pieces within a single log varied from one to three. Typically each cant gave 3 - 5 boards depending on the diameter of the log. The position of every board was recorded relative to the pith and numbered from 1 to 4 as shown in Figure 3.1b. A total of 915 boards from the forty eight trees (144 log) were filleted and air dried to approximately 12% moisture content.

a)

b)

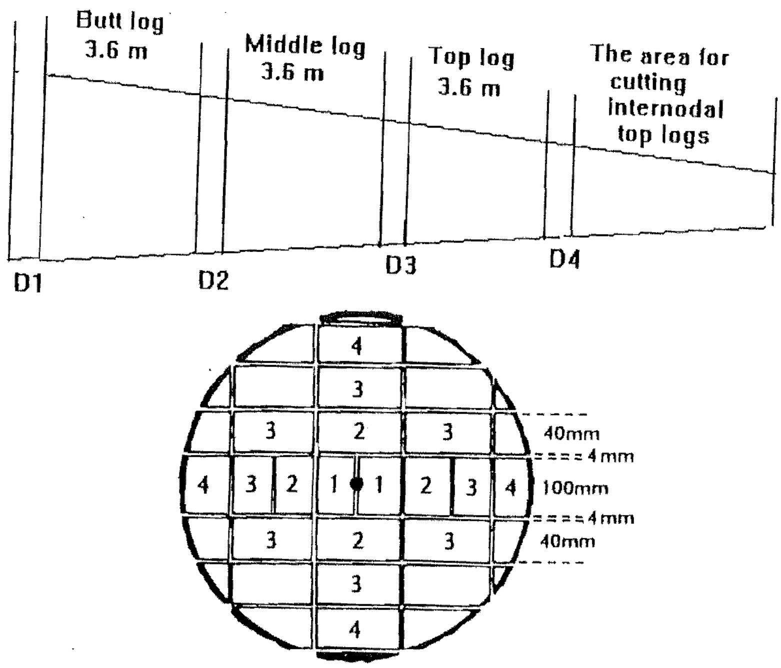


Figure 3.1 (a) **The pattern of cross-cutting of logs, discs and short internodal top logs,** (b) **Sawing pattern in which logs generate 1, 2 or 3 pieces of boxed pith.**

3.2.3 Machine stress grading

After drying the boards were dressed to 90x35 mm and machine stress graded according to the Australian grading rules (SAA 1978a) using a Metriguard continuous lumber tester (CLT), Serial No.19818 which was manufactured by Irvington-Moore, USA.

In a continuous lumber tester (CLT) lumber passes through two bending sections with load cells which apply a force in 3-point loading. The rollers connected to the load cells cause the lumber to be deflected first downward by a fixed amount and then upward by nominally the same fixed amount. The forces required to achieve this bending are measured and then averaged to provide a force measurement which corrects for any kink and bow in the piece. When combining measurements, the force measurement from the first bending section (Load cell 1) is delayed to correspond with the time it takes the same portion of the board to reach the second bending section (Load cell 2).

According to the Australian Standard AS 1749 (SAA 1978b), a mechanically stress-graded timber is any piece of timber to which a stress (F) grade has been assigned by previously established correlation between stiffness and strength. A stress grade designated in a form such as 'F7' indicates that, for such a grade of material, the basic working stress in bending is approximately 7 MPa.

The material for the present experiment was machine stress graded under the normal mill procedures. The minimum E-values assigned by the grading machine to each grade and the spray mark (i.e. given according to the Australian Standard (SAA 1978b), are summarised in Table 3.2.

Table 3.2 **Summary of the spray marks for the machine stress grade and the minimum E-values assigned to each grade.**

	Machine stress grades			
	F4	F5	F8	F11
Colour	Red	Black	Green	Purple
MOE (GPa)	4.14	5.52	8.27	11.58

After stress grading the boards were conditioned indoors for two months before testing. All the 915 machine stress graded boards were used for the tensile testing without any further cutting. All boards were uniform in length, 3.6 m long.

3.2.4 **Preparation of compression test samples**

Full length boards were not tested in compression. Testing was performed on blocks of wood 280 mm long, 90x35 mm in accordance with the size specification given by the Australian/New Zealand Standard AS/NZS 4063:1992.

The compression specimens were cut from boards already tested in tension. After analysing of the stiffness values obtained in the axial tension tests, the forty eight trees were ranked according to the mean stiffness of these boards. It was decided that compression samples be cut from boards which came from the five lowest stiffness trees, five medium stiffness trees and five highest stiffness trees. On the basis of this criterion from a total of 915 boards tested in tension only 286 boards were selected for the cutting of compression specimens.

The decision as to where to cut the compression specimens from the length of boards was made on the basis of the worst visual defect in each piece. The worst defect (i.e. the probable cause of failure) was taken to be a big knot, or a cluster of smaller knots. In the case of boards where there were no knots, other minor defects such as wane were considered. In extreme cases where a board was free of any defect, clearwood was used for the test specimen. The worst visual defect was selected from a zone 2.6 m long as shown in Figure 3.2.

3.2.5 **Preparation of density samples**

For density determination clearwood blocks of 100 mm long, 90x35 mm dimension were cut from all boards tested in tension. A total of 915 clearwood specimens were prepared and all were cut as near as possible to the failure zone as shown in Figure 3.2.

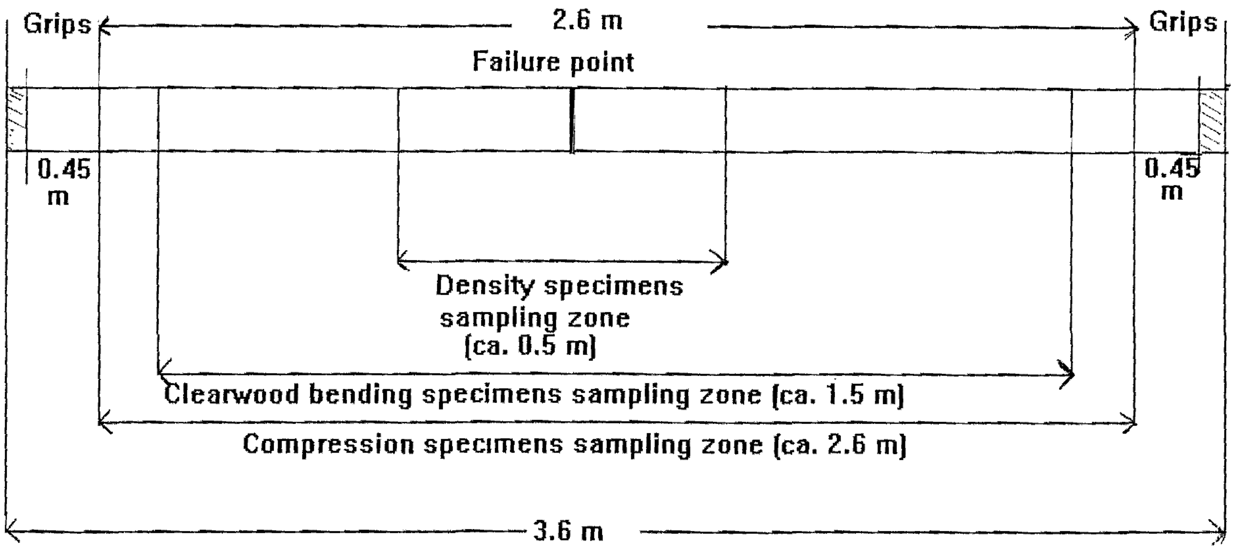


Figure 3.2 **The geometry and pattern of sampling density, clearwood and compression specimens from boards tested in tension.**

3.3 SAMPLE PREPARATION FOR EXPERIMENT II: SMALL CLEAR SPECIMENS

The 300 mm long, 20x20 mm small clear specimens for Experiment II were obtained from two sources: from the 915 boards tested in tension and the 48 small diameter, short length internodal logs from the tops of the trees.

3.3.1 **Preparation of clearwood samples from boards tested in tension**

As described earlier (Section 3.2) after failure in tension small clearwood density blocks were cut from undamaged wood adjacent to the failure zone. Next a piece of timber approximately 0.75 - 1.5 m long containing a clearwood zone of 30 cm or more was set aside for the determination of clearwood properties. Finally, a block for compression tests was cut which contained the worst (usually largest) defect in the board (Figure 3.2). The wood held in the grips during tension testing was excluded from consideration.

Specimens for compression testing of small clear specimens were cut only from boards representing five highest and five lowest stiffness trees as determined in Experiment I (described in Section 3.2.4 above).

The blanks, from which small clearwood specimens were to be cut, were clearwood dressed to 25x90 mm. Each of these 25x90 mm boards were ripped to give two to three 300 mm long 20x20 mm bending specimens. In the case of the extreme value trees, after failure under 3-point loading a 60 mm long specimen for compression tests was cut well clear of the mid-span failure zone. The size and shape of these small clear specimens was in accordance with the British Standard (BS 373:1957). A total of 1830 specimens for bending and 414 specimens for compression testing were prepared.

3.3.2 **Preparation of clearwood samples from the small, short internodal top logs**

The internodal top logs were reduced to a central cant 100 mm thick and two side slabs of variable thickness (25 - 35 mm). Before sawing, logs with reaction wood were distinguished from the logs without obvious compression wood. Logs with stems of cylindrical shape were considered to have normal wood and of the 48 logs only 8 logs were found with such shape (Figure 3.3a). The remaining 40 logs had somewhat swept forms and these were considered to have some compression wood. Again, in order to differentiate the compression wood from the opposite wood, two quadrants of the end grain face were painted, red where it was compression wood and green where it was opposite wood (Figure 3.3b).

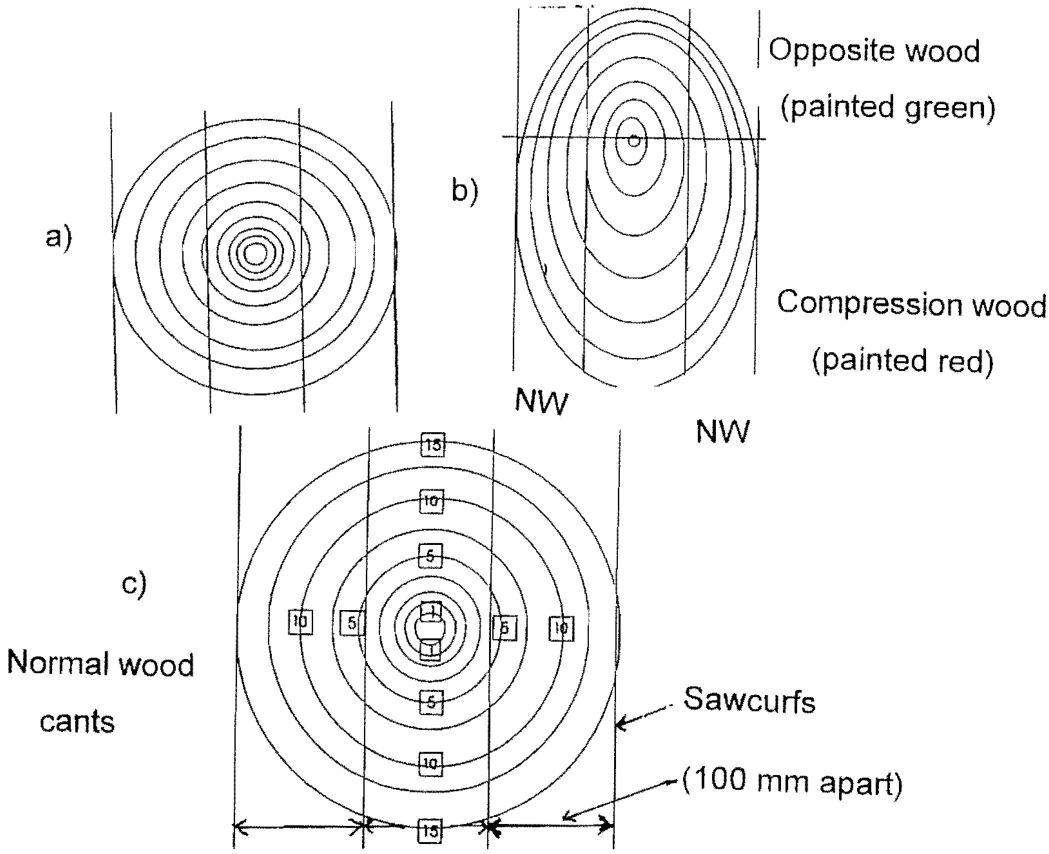


Figure 3.3 **Logs with normal wood (a) were differentiated from those containing compression wood (b). The end-section of the logs having compression wood were painted red in the compression wood gradient and green in the opposite wood gradient. Sampling pattern of clearwood specimens from 1st, 5th, 10th and 15th growth rings (c).**

During sawing:

1. Those logs with compression wood were held between two toothed-end clamps so that the first saw cuts were parallel to compression/opposite wood;

2. In the case of logs with normal wood the orientation of the logs with respect to the plane of the saw was arbitrary;

3. The logs were then sawn into a central cant 100 mm thick and two opposite side slabs of various thickness (i.e. depending on the size of the log).

After the primary breakdown of each log, the code number of each tree was transferred to its respective cant and to those slabs having sufficient thickness to give a 20x20 mm clear specimen. The rest of the log was discarded. Once all the logs were sawn both ends of each cant and one end of each slab were trimmed with a circular saw to give a clear surface for growth ring counting. Then the appropriate ring numbers were marked and recorded.

All cants were sawn and planed to 50 mm thickness while the slabs were dressed to give ca. 25 - 30 mm thick flitches. Finally, the cants and flitches were fillet stacked for air drying in a conditioning room at 20^0C and a relative humidity of 60%.

Once the samples had dried to 12% moisture content 20x20x300 mm clearwood samples were cut, in accordance with the British Standard (BS 373:1957). Clearwood samples were taken at the 1st, 5th, 10th and possibly the 15th growth ring according to the pattern shown in Figure 3.3c. Since the internodal top logs were small in diameter the number of samples from each log ranged from 4 to 8 with the majority of the logs giving 6 samples.

The sample number, position of growth ring and the nature of wood (normal, compression, or opposite wood) was recorded. From a total of 323 samples, 126 were normal wood, 107 compression wood and 87 opposite wood.

3.4 EQUIPMENT AND TESTING PROCEDURE

3.4.1 Moisture content, density and tree volume determination, and visual grading

3.4.1.1 Moisture content

The moisture content of fifty randomly selected boards was obtained soon after testing the boards in tension. Two moisture content readings were taken approximately 200 mm away from the broken ends of the test sample. Later, moisture content was also measured for each compression test specimen just before testing in compression. In both cases the moisture content was measured using an electrical resistance moisture metre, Protometer Model D 184T. The probe was embedded to a depth approximately 1/4 to 1/3 of the specimen depth. The average of the two readings was taken for tension samples and one reading for the compression samples. The overall mean moisture content for the samples was 11.9%.

3.4.1.2 Density

The unextracted air-dry density (at 12 M.C) of each 100 mm long, 90x35 mm clearwood block from Experiment I was determined by Archimedes' displacement method. After measuring the weight each block was dipped in a bath of hot wax. Then the waxed block was submerged in a bucket of water which was already on top of a scale. The scale was zeroed prior to immersion of each block into the water. The sample was held firmly at the centre of the beaker so that it should not touch either side, just keeping it under the water level using a long needle. Finally, a reading of the weight of the displaced water (g) was taken. The additional small volume of the blocks due to wax was deducted prior to the density calculation. The result of an experiment conducted on 10 randomly selected blocks showed that 50% of the wax was absorbed by the end grain and the remaining 50% contributed to the additional volume by each block. Furthermore, the density of the paraffin wax used in the current experiment was also determined: 1 g of wax was equivalent to 1.125 cc of water. Hence the density (kg/cu.m) of each block was calculated using the following formula, incorporating the additional volume of each block due to wax:

$$\text{Density} = \{W_b/((V_{bw}) - 0.5(W_w \times 1.125))\}$$

Where:

W_b = weight of block (g)

V_{bw} = volume of block+wax (cc)

W_w = weight of wax (g)

The density (kg/cu.m) of small clear specimens in Experiment II was determined from the direct measurement of weight, length, width and depth:

$$\text{Density} = W/Lbd$$

where:

W = weight of specimen (g)

L = length of specimen (mm)

b = width of specimen (mm)

d = depth of specimen (mm)

3.4.1.3 **Tree volume**

The volume of each of the 48 trees used in this study was estimated from the four 50 mm thick discs cross-cut at the butt end of each of the 3 logs and the top ends of top log during the selection of research material (Section 3.2.1).

Two diameter measurements (at right angles to each other) were taken for each disc, and the average of the two was taken as the diameter of the disc. From these diameter values the cross-sectional area of each disc was calculated using the following formula:

$$A = \pi D^2/4$$

Where:

A = area (m^2)

D = diameter (m)

Before calculating the volume, the average of the cross-sectional areas of the two middle discs was taken to represent the mid-point cross-sectional area of the tree. The volume of the individual tree was calculated using Newton's formula as follows:

$$V = [(B_b + 4B_{1/2} + B_s)L]/6$$

Where:

V = volume (m^3)

B_b = cross-sectional area of disc at the butt end of the tree (m^2)

$B_{1/2}$ = cross-sectional area of disc at the mid-point length (m^2)

B_s = cross-sectional area of disc at the top end of the tree (m^2)

L = length of the tree (i.e. total length of three logs, 3 x 3.6 m + total thickness of four discs, 4 x 0.05 m = 11.0 m).

3.4.1.4 **Visual grading**

The material for Experiment I was visually graded just after failure in tension. The visual grades were assigned using the knot area ratio principle at the failure point in accordance with the New Zealand Timber Grading Rules (NZS 3631:1988): for No.1 Framing grade, a knot area not exceeding one-third of the cross-section; for No.2 Framing grade, the knot area not exceeding one-half of the cross-section, and for Box grade, any piece whose knot area exceeded one-half of the cross-section.

A summary of the visual grade distribution for all the machine stress graded timber is shown in Table 3.3.

Table 3.3. **Summary of the grade distribution in all the nine hundred and fifteen test boards.**

Visual grades	Machine stress grade				Total
	F11	F8	F5	F4	
Box	-	2	107	85	194
No.2F	-	16	163	29	208
No.1F	11	161	323	18	513
TOTAL	11	179	593	132	915

3.4.2 **Measurement of distance from pith**

In order to determine the actual distance from the pith (mm) of each board tested in tension, a 25-mm long biscuit from the top end of each board was cut. The distance from the pith was measured using the method described by Booker (1987).

To record the annual ring distance and orientation Booker (1987) assumes that a board is sawn from an idealised log of circular cross-section, whose pith is located exactly in the centre. The position of the board with respect to the annual rings within the board can be described by two coordinates as shown in Figure 3.4a. The centroid (C) of the board cross-section can then be defined by two polar coordinates, a radius (r) and an angle (θ).

To record the r and θ coordinates of a board a specially marked transparent overlay (Figure 3.4b) was placed over the cross-section of each board. The transparent overlay has a centre line along its longitudinal axis with concentric arcs centred at one end of the overlay (corresponding to position of the ring from pith). Each arc is numbered indicating its radius in centimetres. To measure the distance of a board from the pith, the board's centroid is located first. In the current analysis the annual ring at the centre of the cross-section of each biscuit was used as a reference point during the measurement of distance. Then the transparent overlay was placed over the cross-section (Figure 3.4c) so that the centre line of the overlay passes through the board's centroid. One of the arcs of the overlay coincides with the annual ring closest the board's centroid. The length of the radius (r) at the centroid was then read off the overlay.

a)

b)

c)

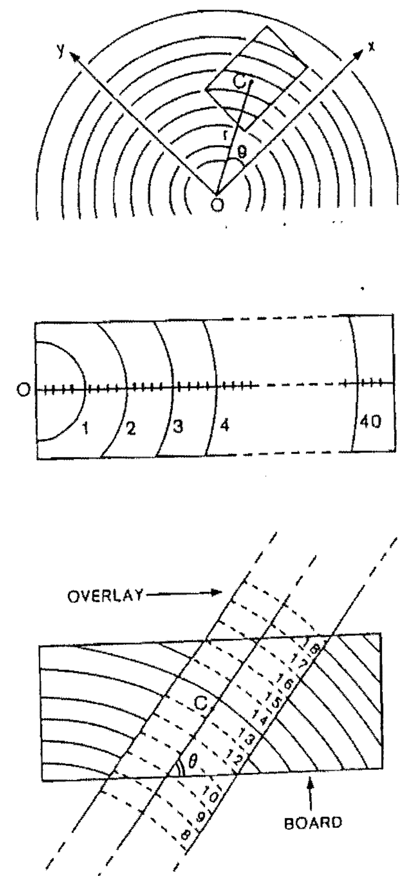


Figure 3.4 (a) **A board cross-section sawn from an idealized log. The x- and y-axes are drawn from the pith parallel to the log and short sides of the board, respectively. The centroid (C) is defined by the polar coordinates (r and θ), (b) diagram of the transparent overlay. O is the centre of the circle arcs, whose radius of curvature is expresses in centimetres, and (c) use of an overlay to determine the coordinates of the centroid (from Booker, 1987).**

A summary of the mean distance from the pith based on the four relative positions from pith is presented in Table 3.4.

Table 3.4 **Summary of mean distance from the pith from the position of the centroidal growth ring of the board, for all boards in one of the four relative positions from pith (as shown in Figure 3.1b).**

Relative position from pith	N	Distance from pith (mm)	
		Mean	standard deviation
1	206	29.3	10.3
2	440	57.1	11.8
3	250	87.8	15.8
4	19	106.8	13.2

3.4.3 **Measurement of spiral grain**

The spiral grain angle for each of the 20x20x300 mm clearwood bending specimens was measured using the technique described by Harris (1989). Of the difficulties in measuring slope of grain for sawn wood, Harris (p. 48) states the following :

> " Sawn timber seldom has faces that are exactly tangential and radial. Grain angles on any surface may therefore reflect sources of grain deviation, and their combined effects are often obscure. To calculate the true slope of grain within a piece, the grain angle on two faces at right angles should be measured".

In this study a ruler and protractor were used to measure grain angles. A base line was drawn parallel to the edge of each specimen using a ruler and the deviation of the grain angle from the base line was measured using a protractor. The grain direction was detected using a magnifying glass, and on frequent occasions the axial resin canals were used to indicate the grain direction. Figure 3.5. clarifies the geometry of measurement. If the slope of the wide face is expressed as the ratio AB:BO, and that of the narrow face as BC:BO, then the combined slope of grain DO is represented by BD:BO. Therefore, in the current measurement combined slope of grain (C) in degrees was calculated using the following formula:

$$C = \sqrt{(F^2 + E^2)}$$

Where:

F = slope of grain on face (degrees)

E = slope of grain on edge (degrees)

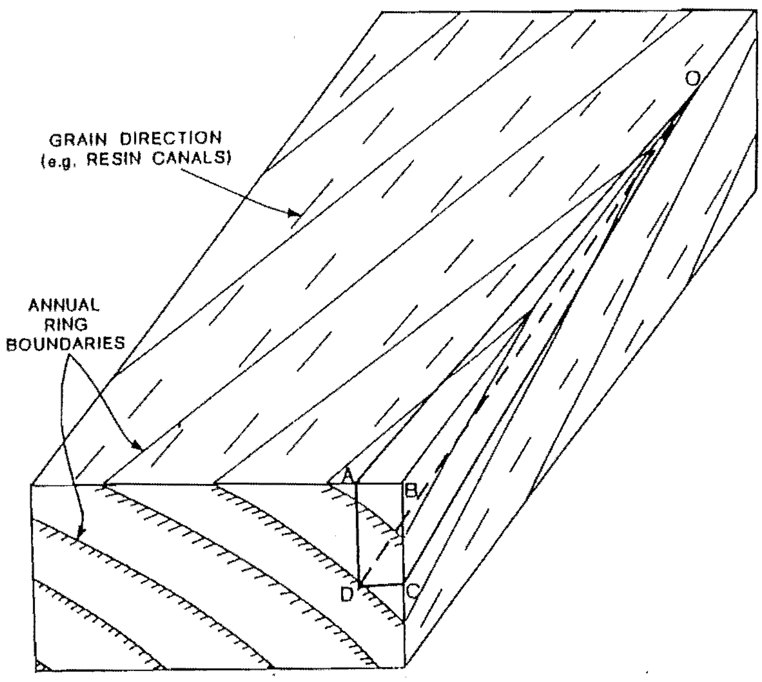


Figure 3.5 **Measuring of the slope of grain in sawn timber (from Harris, 1989).**

3.4.4 **Testing procedure**

3.4.4.1 **Stiffness in bending**

Prior to testing in tension, the modulus of elasticity of the boards was measured in flat-wise bending in four-point loading, first by applying a static load of 5 kg at the mid-point to settle the board then adding static loads of 2 kg at the two third-points of a 3.3 m span. The load (kg) and deflection (mm) were simultaneously measured by a transducer and transmitted through a potentiometer connected to a computer. The apparatus of the bending test is shown in Figure 3.6.

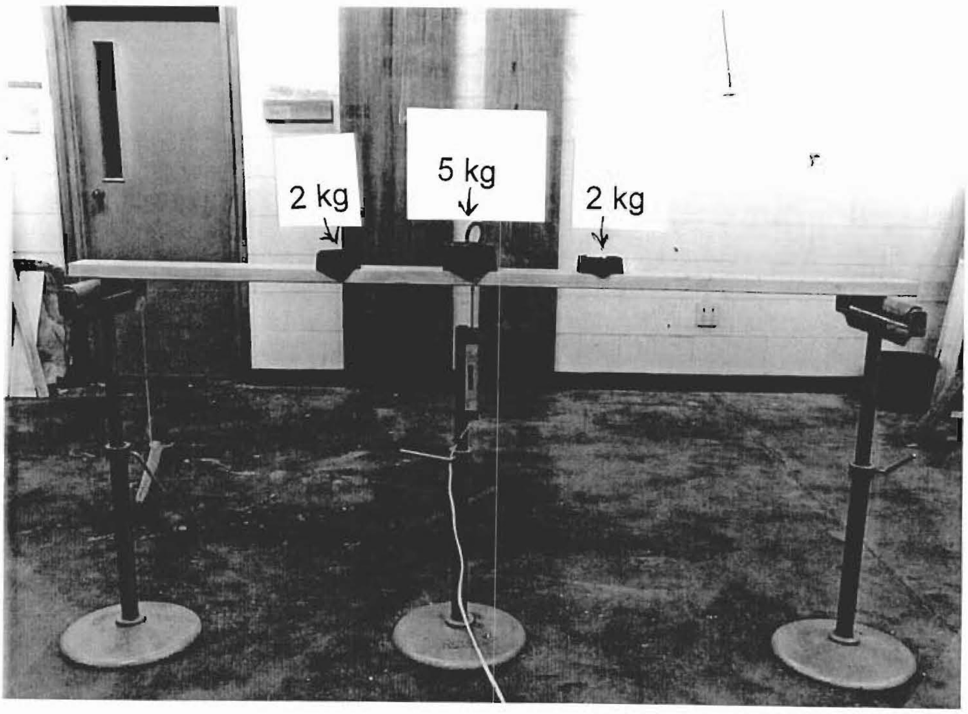


Figure 3.6 **Deflection test apparatus in bending.**

3.4.4.2 **Tension test**

The tensile strength of each board was determined using a horizontal tension test machine which was designed and built at the Department of Civil Engineering, University of Canterbury. The tensile test machine was set up with a distance of 2.6 metres between the two grips 450 mm long. The hydraulically operated grips could apply a uniform gripping force (transverse) up to a maximum of about 90 kN. The tensile force was applied by a 200 kN capacity hydraulic ram which was connected at one end of the test machine. The hydraulic ram was controlled by a manually operated valve. At the other end of the machine a load cell measured the applied force which was continuously captured on a computer.

To avoid damage to the recording transducer, the modulus of elasticity in axial tension was determined under modest loads (< 35 kN), and the equipment was removed before testing to failure. The failure load ranged between 25 kN to 150 kN. The elongation (mm) observed on each specimen was measured by the transducer and potentiometer and recorded on a computer. The whole assembly of the tensile testing machine and the test geometry of the tensile test are presented in Figures 3.7

and 3.8.

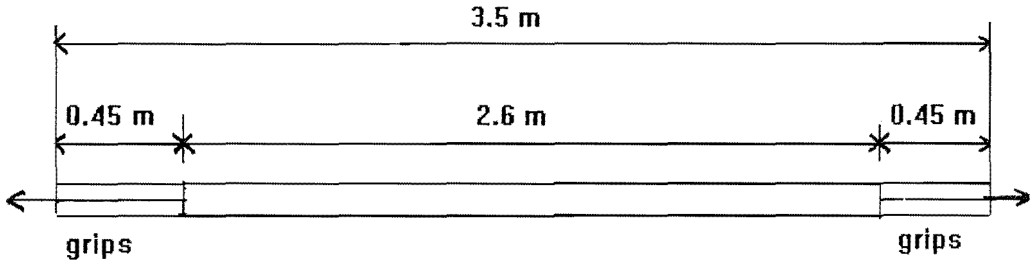


Figure 3.7 **Geometry of in-grade tensile test specimens.**

From the data, the ultimate specimen tensile strength (UTS) and modulus of elasticity (MOE) for tension test samples were computed using the following formulae:

$$UTS = P/bd$$

Where: UTS = ultimate tensile strength (MPa)
P = load causing failure (N)
b = specimen width (mm)
d = specimen depth (mm)

From the axial tension tests,

$$MOE = PL/bdy$$

From the bending test using four-point loading,

$$MOE = PL^3/5.4bd^3y$$

Where: MOE = modulus of elasticity (GPa)
P = load to the proportional limit (N)
L = length of span (mm)
b = specimen width (mm)
d = specimen depth (mm)
y = deflection (mm)

b)

a)

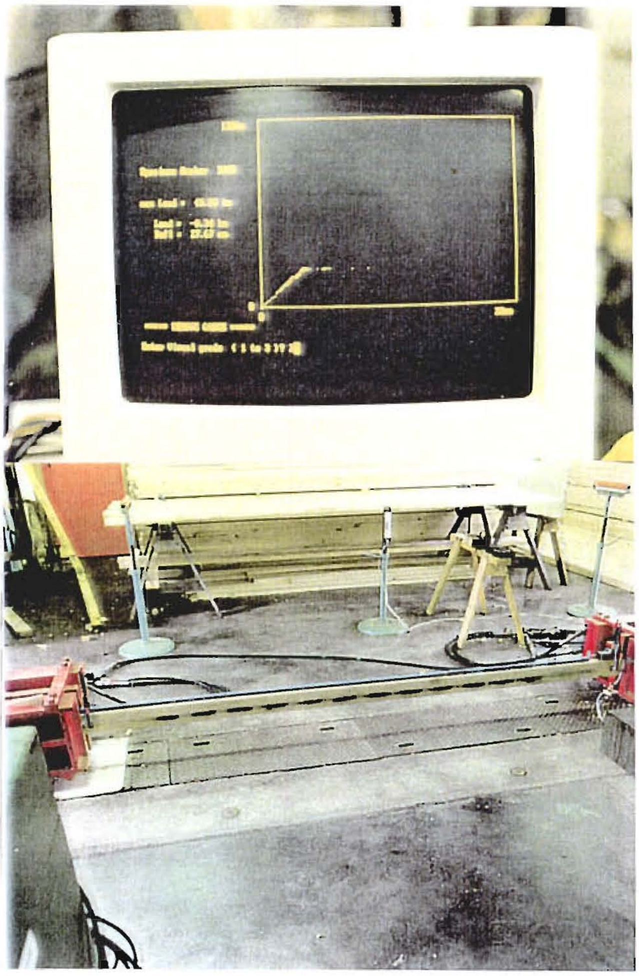


Figure 3.8 **Tension test apparatus: (a) Specimen being pulled between the grips and (b) load-deflection curve on a computer screen.**

3.4.4.3 **Bending test for clearwood specimens**

The bending tests were undertaken on the Instron Model 1195 testing machine at the Wood Technology Laboratory, School of Forestry. The orientation of specimens during testing was such that the load was applied parallel to the growth rings (Figure 3.9). The reason for this choice was so that there is equal amounts of both earlywood and latewood are present on the upper and lower faces of the specimen. The strength at failure, expressed as Modulus of Rupture (MOR), and stiffness expressed as Modulus of Elasticity (MOE) were both calculated from the test data.

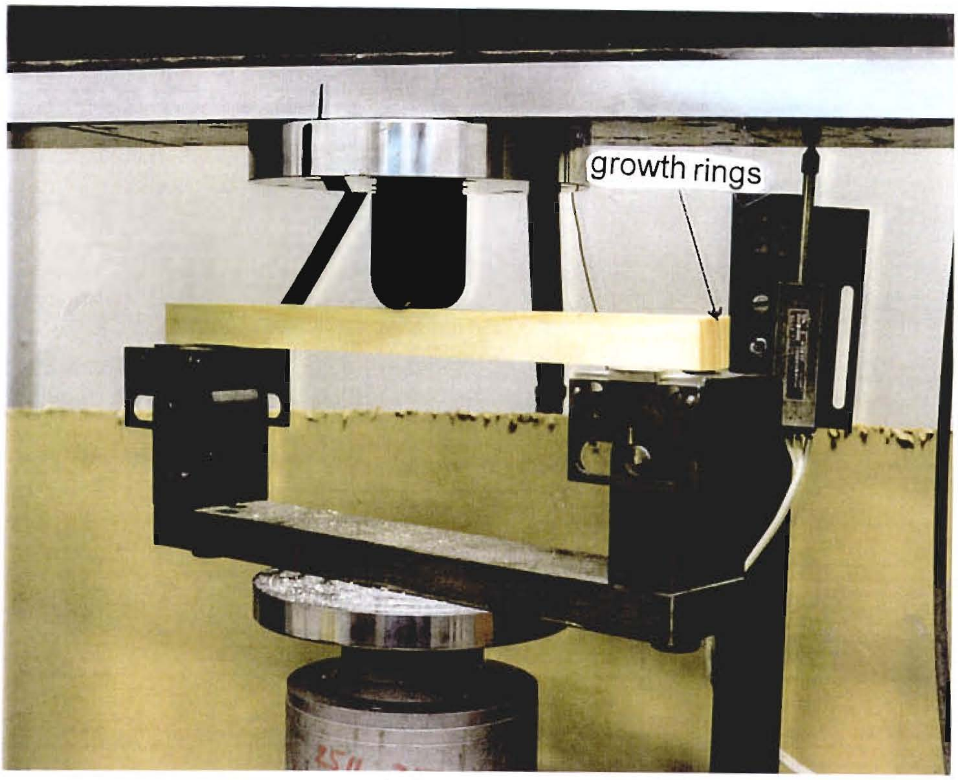


Figure 3.9 **Ring orientation of clearwood specimens during testing in bending.**

To measure both load and deflection, three point loading was applied with a rate of loading of 25 mm per minute. The X - Y plotter output was connected to a computer and the load - deflection data recorded automatically. The MOE was calculated from the load - deflection curve displayed on the computer. The three-point bending test apparatus is shown in Figure 3. 10.

Figure 3.10 **Bending test apparatus.**

From the bending test the Modulus of Rupture and Modulus of Elasticity are computed from the formula below:

$$MOR = 3PL/2bd^2$$

Where: MOR = modulus of rupture (MPa)
P = load causing failure (N)
L = length of span (mm)
b = specimen width (mm)
d = specimen depth (mm)

$$MOE = PL^3/4bd^3y$$

Where: MOE = modulus of elasticity (MPa)
P = load to the proportional limit (N)
L = length of span (mm)
b = specimen width (mm)
d = specimen depth (mm)
y = deflection at the mid-point of specimen (mm)

3.4.4.4 **Compression test**

The compression tests on boards were conducted on the Instron Model 1160 testing machine at the Model Structures Laboratory, School of Engineering, University of Canterbury while the tests on clearwood specimens were conducted on the Instron Model 1195 testing machine at the Wood Technology Laboratory, School of Forestry. The only data recorded was load during testing. The maximum load at the time of failure was used to calculate maximum crushing strength (MCS). The modulus of elasticity was not measured as the value for each specimen had been already determined during the tensile testing.

During testing the cross head speed of the testing machine was 1 mm per minute. The load (P) was automatically recorded. The test apparatus is shown in Figure 3.11.

From the data, the maximum crushing strength (MCS) was calculated using the formula as shown below:

MCS = P/bd

where: MCS = maximum crushing strength (MPa)

P = load causing failure (N)

b = specimen width (mm)

d = specimen depth (mm)

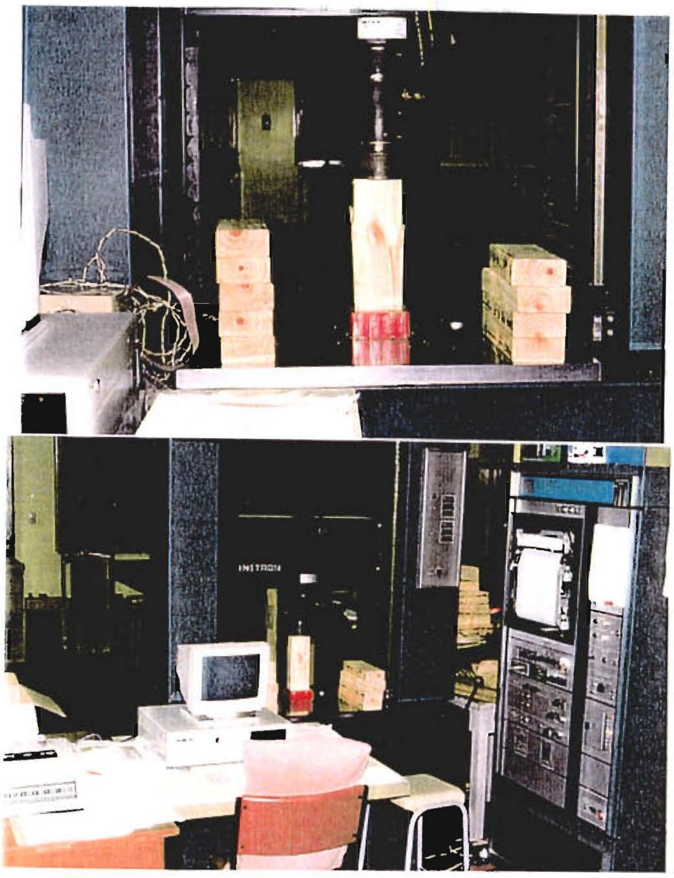


Figure 3.11 **Compression test apparatus.**

PART I: **RESULTS AND DISCUSSION OF EXPERIMENT ONE (IN-GRADE TIMBER)**

CHAPTER 4: **WITHIN- AND BETWEEN-TREE VARIATION**

4.1 **TEST SPECIMENS**

Nine hundred and fifteen boards (3294 linear metres) were proof tested in tension. All the boards had been machine stress graded along their length. The test methods and procedures are described in Chapter 3.

After testing the boards in tension, they were regraded visually on the basis of the knot area ratio at the failure point and the machine and visual grades were recorded for all the boards. A summary of the grade outturn is shown in Table 4.1.

Table 4.1. **Summary of the grade outturn for all boards.**

Visual grades	Machine stress grade				Total
	F11	F8	F5	F4	
Box	-	2	107	85	194
F2	-	16	163	29	208
F1	11	161	323	18	513
TOTAL	11	179	593	132	915

4.2 **WITHIN-TREE VARIATION**

One of the main objectives of this thesis is to address the question of behavioural changes both in the physical and mechanical properties within a single tree when moving from the butt to the top of the tree (vertically) and from the pith to the cambium (radially).

4.2.1 **Grade distribution**

The machine stress grades and visual grades recoveries with respect to the log type and positions of boards relative to the pith are summarised in Tables 4.2 - 4.5.

Table 4.2 **Distribution of machine stress grades within the three log types.**

Log	Machine stress grade				Total
	F11	F8	F5	F4	
Top	-	23	171	27	221
Middle	1	66	195	33	295
Butt	10	90	227	72	399
Total	11	179	593	132	915

Table 4.3 **Distribution of visual grades within the three log types.**

Log	Visual grade			Total
	F1	F2	Box	
Top	103	48	70	221
Middle	166	75	54	295
Butt	244	85	70	399
Total	513	208	194	915

Table 4.4 **Distribution of machine stress grades within the four positions relative to the pith.**

Position from the pith	Machine stress grade				Total
	F11	F8	F5	F4	
1	-	5	123	78	206
2	-	48	343	49	440
3	4	114	127	5	269
4	7	12	-	-	19
Total	11	179	593	132	915

Table 4.5 **Distribution of visual grades within the four positions relative to the pith.**

Position from pith	Visual Grade Box	F2	F1	Total
1	90	63	53	206
2	85	104	251	440
3	19	41	190	250
4	-	-	19	19
Total	194	208	513	915

As expected Tables 4.2 - 4.5 show poorer grades on going from the butt log to the top log and from the cambium to the pith.

4.2.2 **Modulus of elasticity, tensile strength and density**

All values for tensile strength, modulus of elasticity and density are presented in Appendix 1A.

4.2.2.1 **Vertical variation**

The mean values of the modulus of elasticity (MOE), ultimate tensile strength and density for all the samples sorted on the basis of log type are presented in Table 4.6.

Table 4.6 **Mean values of modulus of elasticity (MOE), ultimate tensile strength (UTS) and density based on the three log types.**

LOG	N	MOE (GPa) Bending	MOE (GPa) Tension	UTS (MPa)	Density (kg/cu.m)
Top	221	6.7 (1.4)	6.6 (1.7)	15.2 (5.4)	461 (44)
Middle	295	7.0 (1.7)	7.0 (1.7)	17.9 (5.7)	461 (37)
Butt	399	6.8 (2.0)	6.8 (2.1)	20.9 (8.3)	491 (40)
All	915	6.8 (1.8)	6.8 (1.9)	18.6 (7.3)	474 (43)

Values in parentheses are standard deviations.

First note in Table 4.6 that the mean modulus of elasticity determined in the tension test is similar to that in the bending test. The relationship between MOE in bending with that in tension for all the 915 samples is shown in Figure 4.1.

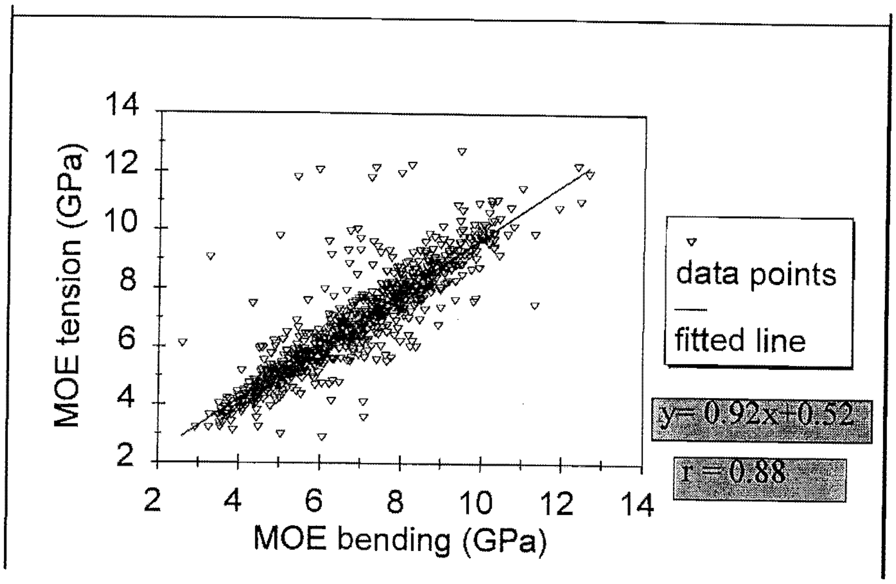


Figure 4.1 **MOE in bending versus MOE in tension.**

Regarding the between-log stiffness, strength and density variations, it can be seen in Table 4.6 that the mean modulus of elasticity changes little (i.e. only 3%) in going from the butt log to the top log. The mean tensile strength decreases steadily by 15% from the butt log to the middle log and by another 15% from the middle log to the top log. The density variation between logs does not follow the pattern observed either in stiffness or in tensile strength. However the butt logs are 6.5% denser than the top logs.

In order to determine the significance of differences between the stiffness and tensile strength values of each log type an analysis of variance test was performed. The results of the analysis of variance test are presented in Tables 4.7 and 4.8.

Table 4.7 **Difference comparison between mean modulus of elasticity (MOE) values of the three log types.**

MOE (GPa)	Log type	Top log	Middle log	Butt log
6.6	Top log	-	*	ns
7.0	Middle log	*	-	ns
6.8	Butt log	ns	ns	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Table 4.8 **Difference comparison between mean tensile strength (UTS) values of the three log types.**

UTS (MPa)	Log type	Top log	Middle log	Butt log
15.2	Top log	-	**	**
17.9	Middle log	**	-	**
20.9	Butt log	**	**	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Discussion

Vertical variations in mechanical properties up the height of the tree were studied by Austin (1988) and Langlands (1938). Austin (1988) examined specific gravity and mechanical properties in dimension lumber cut during a normal mill production from 20- and 50-year-old slash pine (P. elliotti) in the USA. In his study he made a comparison between material cut from butt logs and top logs. For his 20-year-old trees he found that the butt logs were 7%, 51% and 8% higher in specific gravity, modulus of rupture and modulus of elasticity respectively while the respective values for his 50-year-old trees were 15%, 56% and 36% higher.

Langlands (1938) examined specific gravity, bending strength, compression strength and hardness on 20x20 mm clearwood samples sawn from a 22-, 23-, 33- and 52-year-old radiata pine trees. For his specimens taken from the 33-year-old radiata pine trees, he divided the height of the tree into five, 2.4 m sections and made a comparative analysis of changes in bending and compression strength up the height of the tree. His results showed that bending strength was reduced by 2 - 5% in moving from the 2.4 m section to the 4.8 m section, by 5% in moving from the 2.4 m to the 7.2 m section, and by 10% in moving from the 2.4 m section to the 9.6 m section up the height of the tree. For compression strength he observed a much higher overall reduction of 19 - 22% up the tree.

The density variation between logs (Table 4.6) shows that there is a 6.5% difference between the butt log and the top log. This value is close to the 7% to 11% range reported by Cown *et al.* (1991a) for basic density of radiata pine. However, the similarity in the mean density values (i.e. 460 kg/cu.m) between the middle log and the top log is unexpected, as the number of growth layers decreases with increasing height in the stem and a decrease in the mean density would be nominal. Cown and McConchie (1983) in their study of basic density on samples collected from 10 trees of 12-year-old radiata pine from Kaingaroa Forest observed a drop in the mean density of 20 kg/cu.m between the butt and 3-metre height up the stem followed by a decrease of about 10 kg/cu.m for each 3-metre height to the apex. Later in other studies of density on samples collected from 10 trees of 24-year-old and 10 trees of 34-year-old radiata pine Cown and McConchie (1983, 1984) observed a decrease in the mean basic density and extracted air-dry density of 20 - 30 kg/cu.m for each 10-metre height to the apex. This means that in the current study (i.e. with log length 3.6 m) a 5 - 10 kg/cu.m difference in the mean density value might have been expected between the middle log and the top log.

4.2.2.2 Radial variation

4.2.2.2.1 Positions relative to the pith

The mean values for the modulus of elasticity (MOE), ultimate tensile strength and density are shown in Table 4.9 for each position relative to the pith, with all log types aggregated .

Table 4.9 **Mean values for modulus of elasticity (MOE), ultimate tensile strength (UTS) and density based on positions relative to the pith, all log types aggregated.**

POSITION FROM PITH	N	MOE (GPa) in Tension	UTS (MPa)	Density (kg/cu.m)
1	206	5.0 (1.1)	13.5 (3.8)	464 (44)
2	440	6.7 (1.4)	17.8 (5.8)	470 (42)
3	250	8.5 (1.5)	23.2 (8.0)	488 (38)
4	19	9.5 (1.5)	29.1 (9.5)	513 (39)
All	915	6.8 (1.9)	18.6 (7.3)	474 (43)

Values in parentheses are standard deviations.

Table 4.9 shows that there is a general trend for the modulus of elasticity, tensile strength and density to increase in moving from close to the pith toward the cambium.

The percentage increases in modulus of elasticity in moving from position 1 to 2, 2 to 3, and 3 to 4 are 36%, 27% and 11% respectively, and the overall increase from the innerwood (position 1) to the outerwood (position 4) is almost double. The change in the mean tensile strength value follows a similar pattern to that for stiffness. The rate of change between positions 1 and 2 and positions 2 and 3 is 31%, and between positions 3 and 4 is 25%. The tensile strength in the outerwood (position 4) is more than double that from the innerwood (position 1).

An analysis of variance test was performed to determine the potentially significant differences between the stiffness and tensile strength values at each position relative to the pith. The results of the analysis of variance test are presented in Tables 4.10 and 4.11.

Table 4.10 **Difference comparison between mean modulus of elasticity (MOE) values of the four relative positions from the pith.**

MOE (GPa)	Position	1	2	3	4
5.0	1	-	**	**	**
6.7	2	**	-	**	**
8.5	3	**	**	-	**
9.5	4	**	**	**	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Table 4.11 **Difference comparison between mean tensile strength (UTS) values of the four relative positions from the pith.**

UTS (MPa)	Position	1	2	3	4
13.5	1	-	**	**	**
17.8	2	**	-	**	**
23.2	3	**	**	-	**
29.1	4	**	**	**	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

The changes in the mean density from the pith to the cambium correlate with the changes in both the modulus of elasticity and tensile strength. However, the increase from 464 kg/cu.m at position 1 to 514 kg/cu.m at position 4 (i.e. an overall increment of 11%) cannot be considered large.

The 11% increase in density from position 1 to position 4 is far lower than the 30 - 40% increase in the first 20 to 30 growth layers from the pith reported by Cown *et al.* (1991a) for extracted density of radiata pine. The smaller difference in the current study between the innerwood (position 1) and outerwood (position 4) could be due to three effects. First the boards at position 1 include wood from up to 7 growth rings from the pith, depending on the location of the pith at each cross section. The density would be lower if wood from only the first two growth increments was considered. The second reason could be resin infiltration near the pith. The third reason could be site related. The Canterbury Region is classified as a low-density site and the increment in density in low-density sites may be lower than the high-density sites (Cown *et al.* 1991a).

The two fold increases in modulus of elasticity, tensile strength and the 11% increase in density from the innerwood to outerwood for all the logs aggregated (Table 4.9) are lower compared with the results of Bendtsen and Senft (1986) who examined radial variation in specific gravity, cell length, fibril angle and mechanical properties on micro-specimens cut from 30-year-old cotton wood and loblolly pine trees. For example, for their loblolly pine specimens they found a five fold increase in the mean modulus of elasticity, a three fold increase in the mean modulus of rupture and only a 40% increase in the mean specific gravity from early juvenile (ring 1) to late mature wood (c. ring 30).

However, in order directly to compare Bendtsen and Senft's data for loblolly pine with that of the current study for radiata pine, the number of growth rings for loblolly pine should be volume averaged to be equivalent to wood in a piece of 90x35 mm containing a number of growth rings. The number of growth rings in a 90x35 mm wood ranges up to 7. Hence if we volume average and compare the values for rings 1 - 6 with those of rings 15 - 22 (which is typical of the wood in the current study), the increase from innerwood (rings 1 - 6) to outerwood (rings 15 - 22) of loblolly pine will be lowered to 35 percent in specific gravity, to 3.6 fold in modulus of elasticity and 2.3 fold in modulus of rupture. This innerwood-to-outerwood variation for loblolly pine is still a little higher than that for radiata pine in the current study, but it is a different species growing in a different geographic region.

Table 4.12 shows the same data presented in Table 4.9 for modulus of elasticity and ultimate tensile strength for each position relative to the pith, but segregated according to log type. This pattern of variation in the mean values of the modulus of elasticity and tensile strength within a tree is also presented in Figure 4.2.

Table 4.12 **Mean values for modulus of elasticity (MOE) and ultimate tensile strength (UTS) based on positions relative to the pith, segregated according to log type**.

LOG	POSITION FROM PITH	N	MOE (GPa)	UTS (MPa)
Top	1	58	5.3 (1.3)	11.9 (3.9)
Middle	1	65	5.2 (0.8)	14.2 (3.1)
Butt	1	83	4.5 (0.9)	14.2 (3.8)
Top	2	120	6.7 (1.2)	15.8 (5.3)
Middle	2	145	6.8 (1.3)	17.2 (4.5)
Butt	2	175	6.5(1.6)	19.7 (1.6)
Top	3	43	8.2 (2.0)	18.0 (5.7)
Middle	3	83	8.6 (1.2)	21.8 (6.5)
Butt	3	124	8.5 (1.5)	26.0 (8.4)
Middle	4	2	8.5	26.8
Butt	4	17	9.6 (1.5)	29.4 (10.0)
All		915	6.8 (1.9)	18.6 (7.3)

Values in parentheses are standard deviations.

It can be seen from Table 4.12 and Figure 4.2 that both the modulus of elasticity and tensile strength vary over the cross-section and up the stem. In the butt log there is more low stiffness timber in positions 1 and 2 and more high stiffness timber in positions 3 and 4. Hence, compared to the middle log and the top log (Tables 4.2 and 4.3) the grade outturn for the butt log is more variable (with 18% F4 and below and 25% F8 and better for the machine stress grades, and 48% of No.1 Framing grade and 36% of Box grade for visual grades).

Table 4.13 shows the ratio between mean modulus of elasticity and tensile strength. It can be seen that the ratio increases steadily from the butt log to the top log but within each log type the ratio is essentially constant over the cross section.

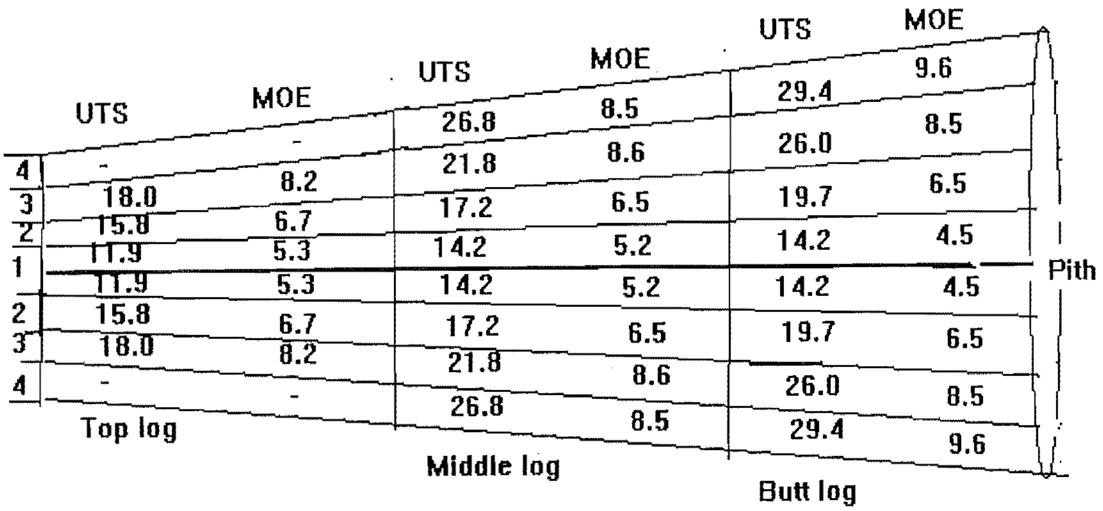


Figure 4.2 **Within-tree variation of modulus of elasticity and tensile strength.**

Table 4.13 **The ratio of mean modulus of elasticity (MOE) to mean ultimate tensile strength over the cross-section of the stem.**

Log	Position relative to the pith			
	1	2	3	4
Top	444	422	454	--
Middle	370	398	393	--
Butt	317	330	326	327

Discussion

The general pattern of change for both the modulus of elasticity and tensile strength for the four positions across the radius is shown in Figure 4.3 with all log types aggregated. The ellipses are centred at the mean values for the modulus of elasticity and tensile strength from Table 4.9, with 90% of all the data points lying within each ellipse. A linear regression analysis performed between the modulus of elasticity and tensile strength values gave an R-squared value of only 0.32 for the entire 915 boards. This value indicates that there is a very poor correlation between the modulus of elasticity and tensile strength. An R-squared value of 0.32 means that only 32% of the variability in tensile strength can be explained by the modulus of elasticity and the other 68% of the variability is due to other factors.

The poor correlation (R-square value of 0.32) between the values of the modulus elasticity and tensile strength is similar to the results of Addis Tsehaye (1989) who obtained a value of 0.30 between the modulus of elasticity and tensile strength in study of a 90x45 mm boxed-pith radiata pine from Nelson province in New Zealand and to that of Anton (1979) who obtained an R-square value of 0.36 between the modulus of elasticity and modulus of rupture in his study of 70x35 mm timber sawn from 13-year-old thinnings of radiata pine from Myrtleford, Victoria in South Australia. These values should not be compared directly with the R-square value of 0.65 obtained by Walford (1982) in his study of 100x50 mm timber of radiata pine in New Zealand. He obtained this value by superimposing two completely different sample populations selected on the basis of density: the ranges of density being 269 kg/cu.m to 404 kg/cu.m for one batch, and 443 kg/cu.m to 456 kg/cu.m for the second. The very weak correlation coefficients found in this study and the earlier work by Addis Tsehaye (1989) and Anton (1979) reflect the limited range of modulus of elasticity and strength values in the sample populations, due in part to the relative immaturity of the timber. This raises questions regarding the use of machine stress grading for such young timber. A further point arises in the choice of the appropriate regression equation as the ratio of the modulus of elasticity to the tensile strength (Table 4.13) increases up the tree, whereas at each level the ratio is essentially constant over the cross-section.

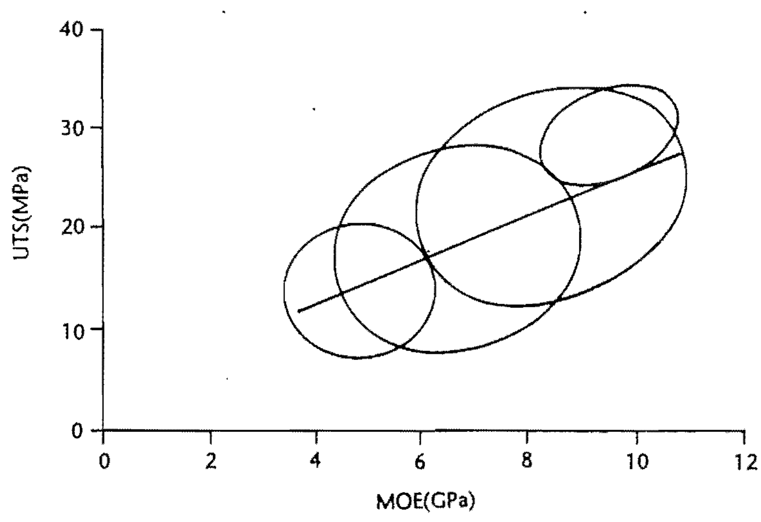


Figure 4.3 **Tensile strength versus modulus of elasticity for the four positions relative to the pith.**

Correlation coefficients of similar magnitude have been observed for other fast grown softwood species. For example, Kretschman and Bendtsen (1992) in their study of tensile strength and modulus of elasticity with 38 x 89 mm lumber cut from 100 28-year-old plantation grown 100 loblolly pine trees in the USA, obtained an R-squared value of 0.33. They also observed that the slope of modulus of elasticity-tensile strength relation decreased with increasing juvenile wood in moving from the cambium to the pith. Kretschman and Bendtsen (1992) compared their R-square value with previous published values by Doyle and Markwardt (1967) and Green and Kretschmann (1991) who studied the same properties for the southern pines and obtained R-square values of 0.42 and 0.44 respectively.

4.2.2.2.2 **Actual distance from pith**

In order to determine the actual distance from the pith (mm) board, a 25-mm length biscuit was cut from the top end of each board. The distance from the pith was measured using the method described earlier in Chapter 3.

The relationship between actual distance from the pith and the modulus of elasticity, tensile strength and density are presented in Figures 4.4a - c. A linear regression analysis between distance and modulus of elasticity, ultimate tensile strength and density was performed. A summary of the results of the linear regression analysis is presented in Table 4.14.

Table 4.14 **Summary of results of linear regression analysis between distance from pith and MOE, UTS, and density.**

Dependent variable	N	Constant	Coefficient	R-square (%)
MOE	915	3.5	0.1	59.8
UTS	915	8.5	0.2	33.3
Density	915	449	0.4	6.3

Table 4.14 indicates that there is a moderately strong relationship between distance and modulus of elasticity. The R-square value indicates that almost 60% of the variability in the modulus of elasticity is dependant or can be explained by radial

a) b) c)

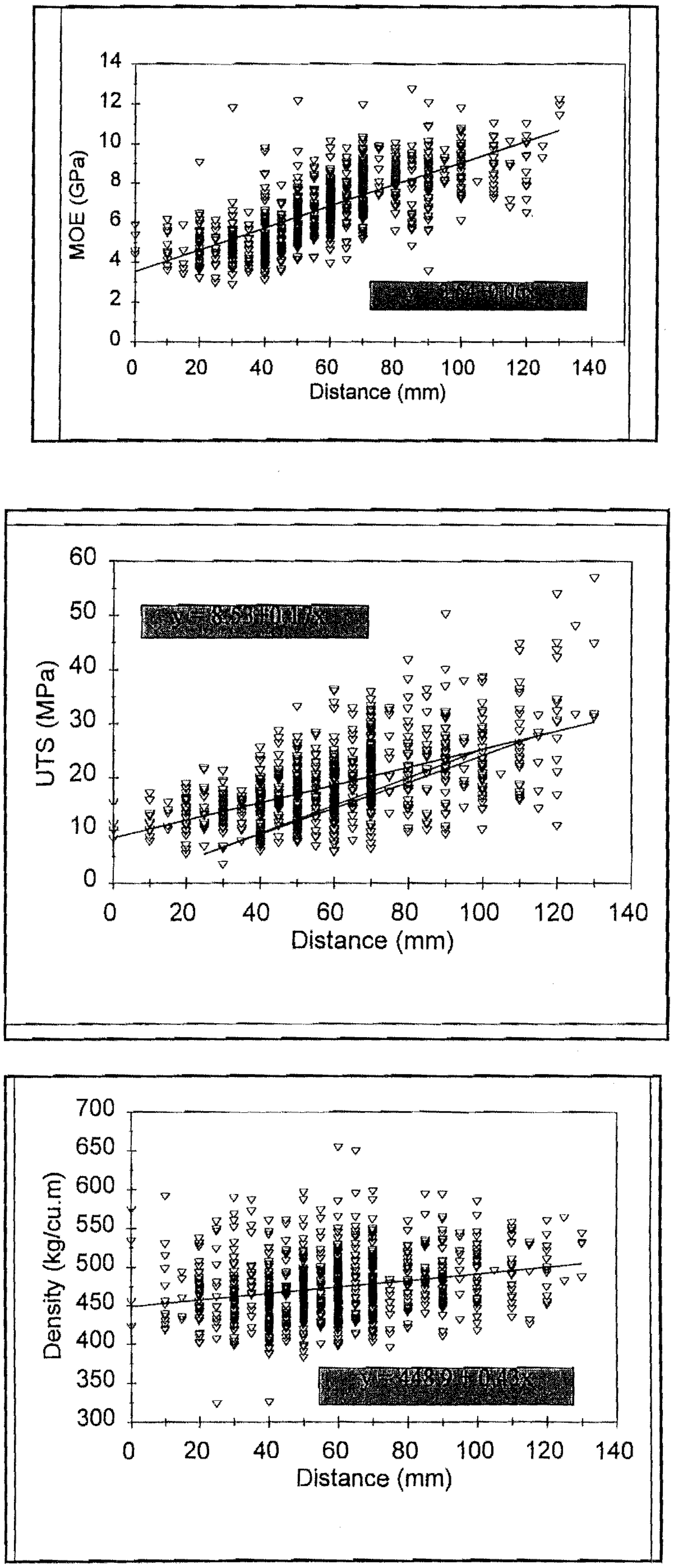


Figure 4.4 **Distance from the pith versus (a) MOE, (b) UTS and (c) Density.**

distance from the pith. The Table also indicates that there is a modest relationship between distance and tensile strength: only 33.4% of the variability in tensile strength can be accounted for by the radial distance from the pith. The relationship between distance and density is very weak (i.e. R-square value of only 6.3%).

Analysis of variance using SAS (1985) was used to test the significance of the relationship between distance and modulus of elasticity, tensile strength and density. The results from the analysis of variance test show that there is a statistically significant relationship (at 1% significant level) between distance and modulus of elasticity, and between distance and tensile strength (although the regression between distance and tensile strength was not strong). However, there is no significant relationship between distance and density.

Tables 4.9 and 4.12 and 4.13 clearly show the effect of radial distance from the pith on both modulus of elasticity and tensile strength. The greatest change observed in going from the pith to the cambium in the stiffness values (36%) and in tensile strength values (31%) occurred between positions 1 and 2 (Figures 4.4a and b), in line with the observation of Bendtsen(1978) namely "the rate of change in most properties is very rapid in the first few rings, the later rings gradually assume the character of mature wood".

4.2.3 **Compression Strength**

4.2.3.1 **Test specimens**

A total of two hundred eighty six 280 mm long, 90x35 mm samples were used for the compression test. These samples were selected on the basis of the ranking of the trees according to stiffness: samples were taken from only fifteen trees the five low stiffness, five medium stiffness and the five high stiffness trees. The procedure for ranking according to stiffness will be discussed later in Section 4.4 of this thesis. This ranking means that sampling was not a random sampling procedure as in the case of tensile specimens. The systematic sampling procedure will have the effect of severely limiting the number of values clustered about the central part of the distribution.

The compression samples, as indicated earlier (Chapter 3) were cut from boards which had already been tested in tension. The samples were selected to contain the worst defect i.e. the largest knot or cluster of knots, within the unbroken parts of the tensile test board. As the failure in tension occurred at the worst available defect along the length of a board, it is obvious that the compression specimens represented only the next worst defect on the board. For this reason the compression results of this experiment should be treated with caution as they will probably be higher than in a normal situation (i.e. in a situation where specimens were selected before any boards were tested in tension).

4.2.3.2 **Results**

All values of compression strength are presented in Appendix 1B. A summary of results for the mean compression strength based on the three log types and the four positions relative the pith is presented in Tables 4.15 and 4.16.

Table 4.15 **Mean compression strength (MCS) based on log types.**

Log	N	MCS (MPa)
Top	72	25.8 (6.1)
Middle	90	26.1 (5.6)
Butt	124	26.5 (5.4)
All	286	26.1 (5.8)

Figures in parenthesis are standard deviation.

Table 4.16 **Mean compression strength (MCS) based on relative positions from the pith.**

Position from pith	N	MCS (MPa)
1	61	24.1 (4.9)
2	140	25.7 (5.4)
3	78	27.9 (6.4)
4	7	30.7 (4.2)
Total	286	26.1 (5.8)

Figures in parenthesis are standard deviation.

Discussion

Table 4.15 shows that in going from the butt log to the top log there is a very modest increase in the mean compression strength. The increase between the butt log and middle log is 1.5%, and that between the middle log and top log is 1.2%. The overall increase between the butt log and the top log is 2.7% which is much less than that for the tensile strength, where the overall change was 37.5%, but is slightly higher than the overall changes observed for the modulus of elasticity which was only 3% (Tables 4.6 and 4.9).

In the case of the values for positions relative to pith (Table 4.16), it can be seen that there is a general trend of increasing compressive strength in moving from one position relative to the pith to the next. The percentage increases in compression strength in moving from position 1 to 2, 2 to 3, and 3 to 4 are 6.4%, 9.2% and 9.6% respectively. The overall change in the mean compression strength between the wood adjacent to the pith (position 1) and wood near the cambium (position 4) is 27.5%. This value is much less than that observed for tensile strength which was more than double between the two extreme positions.

An analysis of variance test to determine significant differences between the mean compression strength values of the three log types and four relative positions from the pith was performed. The results of the analysis of variance test are presented in Tables 4.17 and 4.18.

Table 4.17 **Difference comparison between mean compression strength (MCS) values of the three log types.**

UTS (MPa)	Log type	Top log	Middle log	Butt log
25.8	Top log	-	ns	ns
26.1	Middle log	ns	-	ns
26.5	Butt log	ns	ns	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Table 4.18 **Difference comparison between mean compression strength (MCS) values of the four relative positions from the pith.**

MCS (MPa)	Position	1	2	3	4
24.1	1	-	*	**	**
25.7	2	*	-	**	**
27.9	3	**	**	-	**
30.7	4	**	**	**	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

4.3 BETWEEN-TREE VARIATION

4.3.1 Procedures for ranking

Differences in the mean modulus of elasticity, tensile strength and density between the individual trees were examined by ranking the mean modulus of elasticity, tensile strength and density values of the 48 butt logs separately. The 48 trees were divided into three groups. Two groups represent the five low and five high extreme value trees, and a large third group represents the medium value trees.

Note that the between-tree comparison in this thesis is made only on the basis of average values of stiffness, strength and density of timber or clearwood taken from the individual trees, but not on the basis of whole tree mechanical test results.

Rankings according to stiffness and tensile strength differ slightly from one another. Three of the low stiffness trees were also amongst the five weakest trees, whereas only two of the five high stiffness trees also displayed high strength characteristics. Ranking of trees according to density showed a marked difference from that for stiffness and tensile strength. Of the five high density trees, only one of these displayed high stiffness and high strength while another displayed high stiffness. In contradiction one high density tree displayed low stiffness. The rest of the trees in the high and low density groups have stiffness and strength which place them in both the medium stiffness and strength groups. Trees selected according to stiffness, tensile strength and density are summarised in Table 4.19.

Table 4.19 **Summary of trees selected according to stiffness, tensile strength and density.**

Property	Group (five trees in each group)	
	Low value trees	High value trees
Stiffness	#5, #25, #16, #18, #2	#24, #3, #28, #11, #41
Strength	#5, #25, #16, #46, #47	#24, #3, #21, #22, #35
Density	#12, #32, #45, #26, #48	#24, #5, #28, #29, #37

= identification numbers (1 - 48) given to the 48 trees.

4.3.2 Ranking of trees according to stiffness

4.3.2.1 Modulus of elasticity and tensile strength

The mean values of modulus of elasticity and ultimate tensile strength for the five low stiffness trees, thirty eight medium stiffness trees and five high stiffness trees are summarised in Table 4.20. Ranking results presented here are on the basis of data from the butt logs only. Results for all log types are presented in Appendix 4.

Table 4.20 **Mean modulus of elasticity and ultimate tensile strength for the three groups of trees ranked according to stiffness: data from the butt logs only.**

Group	# of trees	# of boards	MOE (GPa)	UTS (MPa)	Density (kg/cu.m)
Low stiffness trees	5	47	4.7 (0.3)	12.1 (3.4)	489 (22)
Medium Stiffness trees	38	311	6.5 (0.8)	20.2 (2.7)	486 (27)
High stiffness trees	5	41	8.4 (0.6)	25.7 (1.1)	527 (27)

Values in parentheses are standard deviation.

Table 4.20 indicates the potential increase in stiffness and strength if one were able to select seedlings on the basis of stiffness at the time of planting or thinning. From the mean values shown in Table 4.20 it can be seen that there are large differences between the two extremes i.e. the stiffest trees are almost 80% stiffer than the least stiff trees and the stiffest trees are more than double the strength of the least stiff trees. Even the difference between the medium stiffness trees and the low stiffness trees is appreciable. The medium stiffness trees are 39.6% stiffer and 66.9% stronger than the low stiffness trees, and 30.0% less stiff and 24.8% weaker than the high stiffness trees. This indicates that irrespective of the low coefficient of correlation observed between the two properties (R-square value of 0.32, Section 4.2), modulus of elasticity can still be considered as a good indicator of tensile strength.

The machine stress grade distributions for the three groups of trees are summarised in Table 4.21.

Table 4.21 **Grade distribution for all the boards from the butt logs, from trees grouped according to stiffness.**

Group	# of trees	# of boards	F4 (%)	F5 (%)	F8 (%)	F11 (%)
Low stiffness trees	5	47	38.3	51.1	10.6	0.0
Medium stiffness trees	38	311	16.7	59.8	22.8	0.7
High stiffness trees	5	41	4.9	41.5	34.1	19.5

If one were to select trees having properties corresponding to those of the stiffest 10% of trees rather than of the medium stiffness trees this would raise the quality of the timber by at least one grade. Table 4.21 indicates how the grade recovery improves with improving quality of material. This improvement in stress grade recovery is expected because the machine stress grade is obtained directly from stiffness measurements. The causes of such a variation in characteristics between trees within the same stand is the object of future investigation.

4.3.2.2 **Compression strength**

It has already been indicated (Section 4.3) that the compression specimens were selected on the basis of ranking of trees according to stiffness. However, boards from all the three logs from 15 trees were used, selecting the five low stiffness trees and five high stiffness trees, and only five medium stiffness trees.

A summary of the mean values of compression strength for the five low stiffness trees, five medium stiffness trees and five high stiffness trees is given in Table 4.22.

Table 4.22 **Mean compression strength (MCS) for the three groups of trees ranked according to stiffness: data from all log types.**

Group	# of trees	N	MCS (MPa)
Low stiffness trees	5	110	24.8 (5.6)
Medium stiffness trees	5	79	25.9 (5.7)
High stiffness trees	5	97	27.8 (5.6)
Total	15	286	26.1 (5.8)

Figures in parenthesis are standard deviation.

Table 4.22 shows that there is a gradual trend of increasing compression strength in moving from low stiffness trees to high stiffness trees. However, the 12.2% increase in compression strength between the low stiffness and high stiffness trees is much less than the more than two fold increase achieved for tensile strength (Table 4.20 above).

4.3.3 **Ranking of trees according to tensile strength**

The mean values of tensile strength and modulus of elasticity for the five weakest trees, thirty eight medium strength trees and five strongest trees are summarised in Table 4.23 below.

Table 4.23 **Mean ultimate tensile strength and modulus of elasticity for the three groups of trees ranked according to strength: data from the butt logs only.**

Group	# of trees	# of boards	UTS (MPa)	MOE (GPa)	Density kg/cu.m)
Weakest trees	5	49	11.3 (3.4)	5.3 (1.0)	496 (27)
Medium Strength trees	38	312	20.3 (2.7)	6.5 (1.0)	487 (27)
Strongest Trees	5	38	27.2 (2.0)	7.7 (0.9)	514 (37)

Values in parentheses are standard deviation.

Table 4.23 shows the effect of ranking trees according to strength. As in the case of ranking according to stiffness, the strongest trees are more than double the weakest trees, but the strongest trees are only 45% stiffer than the weakest trees compared with 80% where sorting by stiffness. The difference in stiffness between the weakest trees and the medium value trees is only 22%, and that between the strongest and medium value trees is only 18%, which are lower compared to the respective 39.6% and 30.0% differences obtained where according to stiffness. This shows that stiffness is a good indicator of strength, whereas strength is a less effective indicator of stiffness.

The machine stress grade distributions for the three groups of trees are summarised in Table 4.24.

Table 4.24 **Grade distribution for all the boards from the butt logs, from trees grouped according to strength.**

Group	# of trees	# of boards	F4 (%)	F5 (%)	F8 (%)	F11 (%)
Weakest trees	5	49	24.5	44.9	26.5	4.1
Medium strength trees	38	312	17.3	60.9	20.8	1.0
Strongest trees	5	38	15.8	39.5	31.6	13.1

Table 4.24 indicates how the grade recovery improves with improving quality of material using strength as a criterion. As expected the grade recovery is good, but not as good as when selecting by stiffness.

4.3.4 **Ranking of trees according to density**

Density has long been considered the best single index of intrinsic wood quality, with well established relationships between density and clearwood properties. The relationship can be described by the following equation:

$$S = K(D)^n \qquad [4.1]$$

where: S = clearwood property (MPa),

D = density (kg/cu.m),

K = a proportionality constant differing for each property and

N = an exponent for each property which defines the shape of the curve.

For example, in the USDA Wood Handbook 1989, Table 4-8 the relationship of density with stiffness (MOE) and bending strength (MOR) is given by the following equations:

$$\text{MOE (MPa)} = 3.13\text{x}10^{6}D^{0.9} \qquad [4.2]$$

$$\text{MOR (MPa)} = 2.56\text{x}10^{3}D^{1.05} \qquad [4.3]$$

Applying equations 2 and 3 above, it can be sen that a density increase of 10% would only increase the stiffness by 9.0% and the strength by 10.5%. However, in New Zealand more emphasis has been given to density than to any other wood property, see Harris (1965, 1975); Cown (1974, 1992a,b); Cown and McConchie (1983, 1984); Cown and Hutchison (1983) and Cown *et al.* (1991a). For example, in a much quoted issue of What's New in Forest Research, Harris (1975) said:

> "One property widely used to assess the usefulness of wood for different purposes is its density. With any one species, timber of high density is stronger than timber of low density".

Bearing in mind such emphasis given to density as an indicator of wood qualities for New Zealand radiata pine, it is essential to undertake a detailed analysis of the experimental results for density in the current study. Hence this section will be divided into two parts:

First, analysis will be made of the results when ranked according to density on data taken from only the butt logs;

Secondly, a regression analysis between density and modulus of elasticity, and between density and tensile strength will be performed for all the 915 boards.

4.3.4.1 **Results from ranking according to density**

The mean values of density, modulus of elasticity and tensile strength for the three groups of trees ranked according to density are summarised in 4.25.

Table 4.25. **Mean density, stiffness and tensile strength for the three groups of trees: data from the butt log only.**

Group	# of trees	# of Boards	Mean Density (kg/cu.m)	MOE (GPa)	UTS (MPa)
Low density	5	42	450 (5.4)	5.9 (0.6)	18.0 (1.0)
Medium density	38	315	489 (20.4)	6.6 (1.1)	20.0 (4.3)
High density	5	42	542 (14.5)	6.8 (1.7)	20.4 (4.5)

Figures in parenthesis are standard deviations.

Ranking of trees according to density gives an indication of the potential benefits when genetic breeding on the basis of density. Table 4.25 shows that by ranking trees on the basis of density only a modest increase in stiffness and tensile strength (i.e. 15% and 13.3% respectively) between the low density trees and the high density trees could be achieved, and there is no significant difference between the medium and high density trees. This is roughly in line with what one would have expected from the USDA Wood Handbook equation (equations 2 and 3) above.

The results of Table 4.25 can be compared with those of Table 4.20 which is ranking according to stiffness (Figure 4.5). If the densities (in Table 4.20) in the three groups are compared with their corresponding strengths one might conclude that an 8% increase in density would result in an increase in strength of between 27% and 112% (obtained by comparing the medium stiffness and least stiff groups respectively with the high stiffness group). This appears to imply a high magnitude of density-strength effect.

The machine grade distribution for the three groups of trees are summarised in Table 4.26.

Table 4.26 **Grade distribution for all the boards from the butt log, from trees grouped according to density.**

Group	# of trees	# of Boards	F4 (%)	F5 (%)	F8 (%)	F11 (%)
Low density	5	42	26.2	66.7	7.1	0.0
Medium density	38	315	16.5	56.2	25.4	1.9
High density	5	42	21.4	52.4	16.7	9.5

The machine grade distribution for the three groups of trees ranked according to density (Table 4.26) shows that the proportion of F4 grade and below is reduced and of F8 and above is increased in moving from the low density to high density groups.

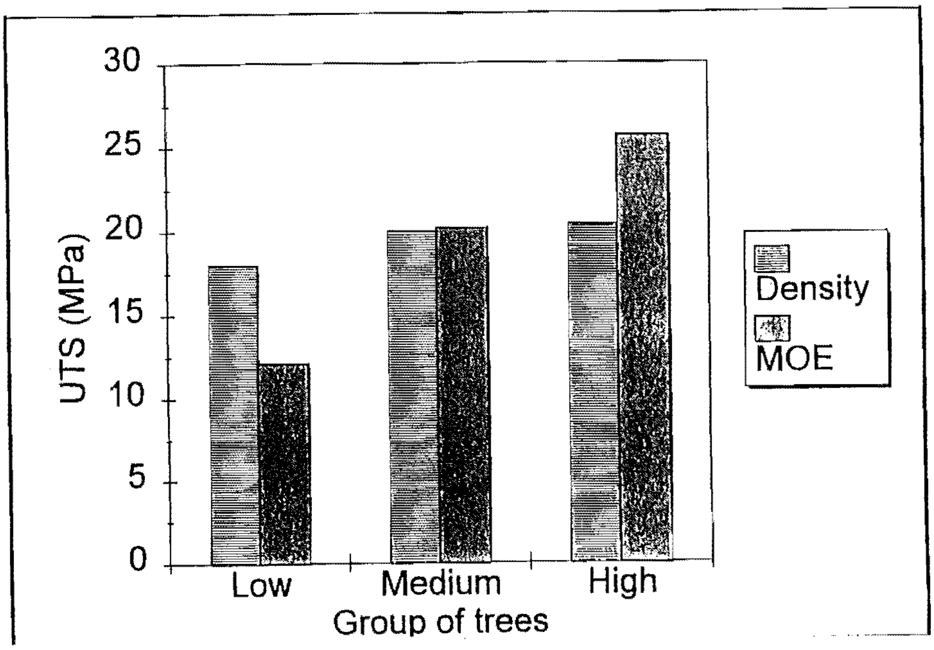


Figure 4.5 **Comparison of ranking according to density versus stiffness.**

Discussion

Generally, Tables 4.20 - 4.26 indicate the potential increases in stiffness and strength properties if one were able to select seedlings on the basis of such criteria (i.e. ranking according to stiffness, strength or density) at the time of planting.

Comparing the grade recoveries with improving quality of material in Tables 4.21, 4.24 and 4.26 with that of the grade recovery of the whole population (Table 4.1) it can be seen that when ranking according to stiffness (Table 4.21) the proportion of F4 and below is greatly reduced from 17% to only 5% and the amount of F8 and above is increased from about 23% to 54% if one were able to select the stiffest trees with the population. This grade recovery is far better compared with that of ranking according to both strength and density. In ranking according to strength (Table 4.24), the proportion of F4 is reduced, only from 17% to 16%, and the proportion of F8 and above is increased to 45%. Again, in the case of ranking according to density (Table 4.26), the proportion of F4 and below is increased to 21%, and the proportion of F8 and above is increased 26%.

One concludes that stiffness is the best single factor and should be considered as such in the future, where structural timber is of interest.

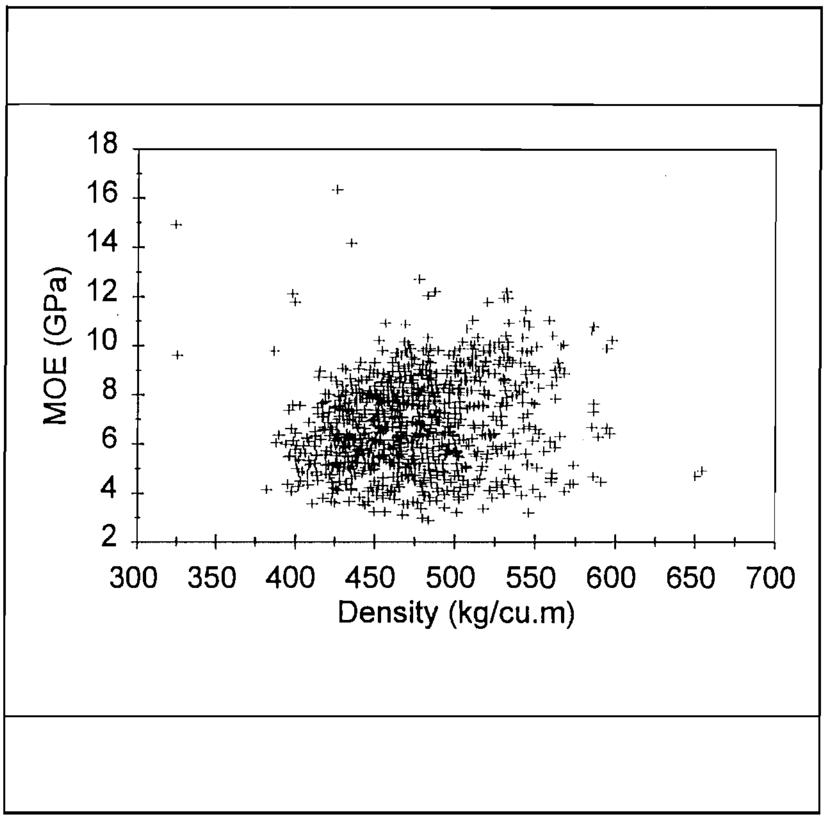
4.3.4.2 **The effect of density on modulus of elasticity and tensile strength**

The relationships between density and modulus of elasticity, and between density and tensile strength for all the 915 are shown in Figures 4.6a and b.

A linear regression between density and modulus of elasticity, and tensile strength shows a very poor correlation (R^2 = 0.06 for modulus of elasticity and R^2 = 0.07 for tensile strength). This means that for all the 915 samples only 6% and 7% of the variability in the modulus of elasticity and tensile strength respectively, can be attributed to density. This shows that density does not have a large effect on both mechanical properties when considering the listed density range in the population of young trees examined in this study.

The regression of density on both stiffness and strength i.e. R^2 = 0.06 and 0.07 respectively, are comparable with the results of Addis Tsehaye (1989) and Bier (1985). Addis Tsehaye (1989) on his study of 90x45 mm boxed-pith material of radiata pine from Nelson Province in New Zealand examined the relationship between density and mechanical properties. In his analysis of the relationship of density with tensile strength, bending strength and compression strength, he observed R-square values of 6 - 10% for tensile strength, 3 - 9% for both bending strength, and compression strength, all tested in three different lengths. Bier (1985)

a)



b)

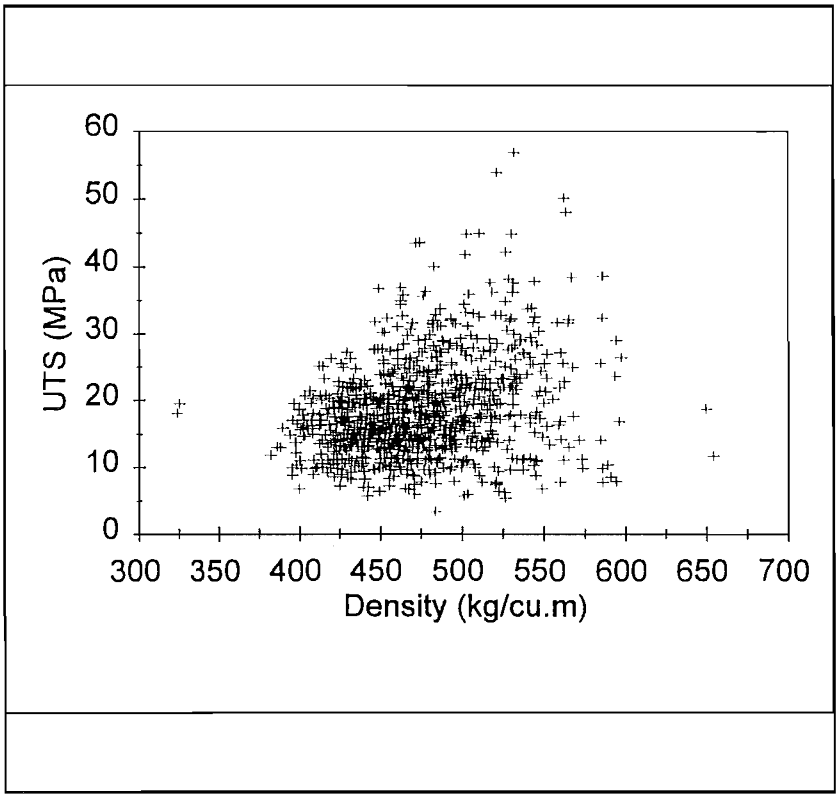


Figure 4.6 **Density versus (a) modulus of elasticity and (b) tensile strength.**

in his study of 100x50 mm and 200x50 mm timber sawn from a 28-year-old radiata pine from Kaingaroa Forest, New Zealand correlated the lower 5-percentile value of bending strength with density and observed R-square value of 16% for the 100x50 mm timber, and 7% for the 200x50 mm timber.

Such poor correlations between density and mechanical properties for radiata pine and other species had already been reported in earlier studies by Langlands (1938), Kloot (1952), Aldridge and Hudson (1958), Manwiller (1972), and Bendtsen and Senft (1986).

Langlands (1938) studied specific gravity, bending strength, compression strength and hardness on 20x20 mm clearwood samples sawn from a 22-, 23-, 33- and 52-year-old radiata pine trees. He reported that even though his results showed a definite correlation between specific gravity and mechanical properties, the degree of relationship was not sufficiently high to enable the mechanical properties of any individual piece to be determined from its density.

Kloot (1952) studied density and tensile strength on 0.08 mm micro-test specimens taken from more than 10 species including radiata pine in Australia. For all specimens taken at various annual rings across the radius of radiata pine trees, he obtained an overall R-square value of 36%. From this he concluded:

> "As several factors may affect the apparent density of specimens without contributing to their strength, it is considered that density variation could not be effectively used for a close study of strength variation".

Similar remarks were made later by Aldridge and Hudson (1958), who examined variation in strength and density on Picea abies They said:

> "When examining the matter of density and strength, many investigators, it seems, have accepted their density readings as a proper indication of the same species. The authors consider that conclusion based up on this assumption is not necessarily true. Inconsistencies occur between density results and strength results".

Manwiller (1972) examined the relationship between specific gravity and mechanical properties on standard sized clearwood specimen cut from 30- and 45-year-old spruce trees in the USA. From his linear regression analysis between specific gravity and mechanical properties, he found R-square values of 0.21 for modulus of rupture and 0.35 for modulus of elasticity and compression parallel to the grain.

Bendtsen and Senft (1986) examined radial variation in specific gravity, cell length, fibril angle and mechanical properties on micro-specimens cut from 30-year-old cotton wood and loblolly pine. For example, for their loblolly pine specimens they found a five fold increase in the mean modulus of elasticity, a three fold increase in the mean modulus of rupture and only a 40% increase in the mean specific gravity from early juvenile to late mature wood. From this they concluded that these changes in specific gravity are not sufficient to account for the increases observed in mechanical properties. The large changes in mechanical properties with age apparently reflect the composite effects of specific gravity, cell length and fibril angle.

The traditional approach to improve wood quality has been to argue in favour of selection on the basis of density. The current study and earlier ones (Walford, 1985, Hadi, 1992) have identified low stiffness to be the principal constraint to greater use of radiata pine for structural purposes. Thus, alternative strategies that approach the problem of low stiffness directly warrant investigation (Cave and Walker, 1994).

CHAPTER 5: **MAIN EFFECT ANALYSIS; GRADE EFFECT**

5.1 MAIN EFFECT ANALYSIS: COMPARISON OF WITHIN- AND BETWEEN-TREE VARIATIONS

In Chapter 4 the effects of within-and between-tree variations i.e. the effects of vertical position along the height of a tree and radial position from the pith, and the effects due to variations between trees on stiffness, tensile strength and compression strength have been examined.

The purpose of the previous analysis was to show the effect of each variable separately. However, it is important to show which variable (trees, log or positions relative to the pith) has a significant effect, and whether there is any interactive effects between these variables on stiffness and strength properties. Such an overall effect of variables might be better seen in a main effect analysis in a two-way analysis of variance test rather than a single factor analysis in a one-way analysis of variance test. In this section, a two-way analysis of variance test, using a General Linear Models Procedure (SAS, 1985) is applied to estimate the overall effects of the main effect variables i.e. trees, log types and positions relative to the pith.

This method of analysis is important for the following reasons:

1. It is possible to determine in percentage the variance component of the variability in stiffness, tensile strength and compression strength due to trees, due to logs, due to positions relative to the pith and the overall effect;

2. The assumption of the model in such analysis is that there is a minimum or no interaction among the main effect variables. However, if there is any interaction it is also possible to determine the significance of this effect; and

3. It is possible to minimise the residual (error) effect, which otherwise would be high in individual analysis.

5.1.1 **Results**

A summary of results for modulus of elasticity, tensile strength and compression strength parallel to the grain from the two-way analysis of variance among trees, among log types, among positions relative to the pith and their interaction is presented in Tables 5.1 - 5.3.

Table 5.1 **Summary of results of analysis of variance for MOE.**

Source of variation	DF	Sum of Squares (SS)	Variance component (%)	Mean Square (MS)	F-value	Pr > F
Trees	47	504.5	15.7	10.7	7.7	**
Logs	2	28.3	0.9	14.2	10.1	**
Position	3	1539.0	47.9	513.0	366.9	**
Trees x Logs	92	241.3	7.5	2.6	1.9	ns
Trees x Pos.	103	78.3	2.4	0.8	0.5	ns
Logs x Pos.	5	79.1	2.5	0.5	0.4	ns
Trees x Logs x Position	153	29.8	1.0	6.0	4.3	*
Model Total	405	2500.4	77.8	6.2	4.4	**
Error	509	711.7	22.2	1.4		
Total	914	3212.0	100.0			

Table 5.2 **Summary of results of analysis of variance for tensile strength.**

Source of variation	DF	Sum of Squares (SS)	Variance component (%)	Mean Square (MS)	F-Value	Pr > F
Trees	47	5048.9	10.2	107.4	3.5	**
Logs	2	4973.5	10.0	2486.7	80.6	**
Position	3	13413.5	27.2	4471.2	144.8	**
Trees x Logs	92	3876.5	7.8	42.1	1.4	*
Trees x Pos.	103	5805.7	11.7	56.4	1.8	*
Trees x Logs x Position	153	700.6	1.4	4.6	0.2	ns
Model Total	405	33818.6	68.3	80.5	2.6	**
Error	509	15713.5	31.7	30.9		
Total	914	49532.2	100.0			

Table 5.3 **Summary of results of analysis of variance for compression strength.**

Source of variation	DF	Sum of Squares (SS)	Variance component (%)	Mean square (MS)	F-Value	Pr>F
Trees	28	1993.9	14.1	142.4	3.3	**
Logs	2	34.3	0.2	17.1	0.4	ns
Position	3	1018.3	7.2	339.4	7.8	**
Trees x Logs	14	1023.8	7.2	36.6	0.8	ns
Trees x Pos.	30	1255.2	8.9	41.8	1.0	ns
Logs x Pos.	5	346.0	2.4	69.2	1.6	ns
Trees x Logs x Position	45	1603.6	11.3	35.6	0.8	ns
Model Total	127	7275.0	51.3	57.3	1.3	*
Error	158	692.4	48.7	43.7		
Total	285	14177.4	100.0			

Position = position relative to the pith; x = interaction; ** = $p < 0.01$; * = $p < 0.05$; ns = not statistically significant.

5.1.2 **Discussion**

First it is interesting to examine the two-way analysis of variance test model in general. Tables 5.1 - 5.3 show that for all properties, modulus of elasticity, tensile strength and compression strength the model contributes a higher percentage (i.e. the percentage of variance component) of the variability than that of the error effect and is statistically significant. For the modulus of elasticity and tensile strength (Tables 5.1 and 5.2) the model contributes 77.8% and 68.3% respectively in the variability. For the compression strength however, the model contributes only 51.3% of the variability.

When we look at the contribution of the effects of each variable in the data (Table 5.1), the variance component (%), positions relative to the pith contribute the highest variability (48%) followed by the error effect (22.2%) which is an effect due to factors such as variability between specimens and experimental errors. The variability due to logs, even though statistically significant contributes the least effect (only 0.9%)

in the data. This is much lower than the contributions by any of the other variables.

The results for tensile strength (Table 5.2) can be compared with those for modulus of elasticity (Table 5.1). For example, the effect of vertical position up the height of a tree is more significant in tensile strength (i.e. 10% of the variance component) while that in stiffness is much less (i.e. only 0.9% of the variance component).

In the case of compression strength (Table 5.3), there are three major features: First, the error effect contributes a higher proportion (48.7%) of the variability of the data. This is unexpected as the sampling procedure was not random as in the case of tensile specimens. The systematic sampling procedure will have the effect of severely limiting the number of values clustered about the central part of the distribution, and this should have reduced the error. Secondly, in compression strength the effect of trees is the highest (14.1%). This is also expected as the selection criterion for the compression specimens is between-tree differences in stiffness. Thirdly, compared with the 47.9% in modulus of elasticity (Table 5.1) and 27.2% in tensile strength (Table 5.2), the effect radial positions do not seem so important in compression strength, i.e. contributing only 7.2% of the variability in the data.

From the observation shown in Tables 5.1 - 5.3 a general conclusion could be drawn that radial variation across the diameter of a tree is a major effect, followed by the variability between trees. The effect of vertical variation along the height of a tree contributes the least effect for both stiffness and strength properties.

5.2 **EFFECT OF MACHINE STRESS AND VISUAL GRADES**

Mean and standard deviation values for the modulus of elasticity, tensile strength and density for the machine stress and visual grades are presented in Tables 5.4 and 5.5. The mean compression strength values for the machine stress grades are presented in Table 5.6.

Table 5.4 **Mean values of modulus of elasticity (MOE), ultimate tensile strength (UTS) and density based on machine stress grades.**

MSG	N	MOE (GPa)	UTS (MPa)	Density (kg/cu.m)
F4	132	4.8 (1.3)	13.1 (4.3)	474 (46)
F5	593	6.6 (1.5)	17.8 (6.3)	468 (41)
F8	179	8.7 (1.2)	24.2 (7.4)	494 (37)
F11	11	10.6 (1.0)	34.6 (9.9)	545 (39)
All	915	6.8 (1.9)	18.6 (7.3)	474 (43)

Values in parentheses are standard deviations.

Table 5.5 **Mean values of modulus of elasticity (MOE), ultimate tensile strength (UTS) and density based on visual grades.**

VISUAL GRADE	N	MOE (GPa)	UTS (MPa)	Density (kg/cu.m)
Box	194	5.6 (1.6)	11.6 (3.9)	473 (47)
F2	208	6.3(1.7)	15.3 (3.3)	468 (38)
F1	513	7.5 (1.8)	22.5 (6.8)	478 (43)
All	915	6.8 (1.9)	18.6 (7.3)	474 (43)

Values in parentheses are standard deviations.

Table 5.6 **Mean maximum crushing strength (MCS)and moisture content with respective standard deviations based on machine stress grades.**

MSG	N	MCS (MPa)
F4	47	21.6 (4.0)
F5	167	25.0 (4.6)
F8	62	31.1 (5.3)
F11	10	34.5 (3.2)
Total	286	26.1 (5.8)

Figures in parenthesis are standard deviation.

Tables 5.4 - 5.6 show that the mean modulus of elasticity, tensile strength and compression strength increase with higher grades. As expected the modulus of elasticity and tensile strength show a very regular pattern of dependency on both machine and visual grades, in that they increase on going from lower to higher grade.

An analysis of variance was performed to test the significance differences between mean modulus of elasticity, mean tensile strength and mean compression strength values of both machine stress and visual grades. The results show that there is a statistically significant difference at 1% significant level between the mean stiffness, tensile strength and compression strength values of each machine stress grade, and visual grade.

CHAPTER 6: THE LOWER 5-PERCENTILE AND CHARACTERISTIC STRESS

6.1 THE LOWER 5-PERCENTILE

All the 5-percentile values of tensile strength and compression strength were calculated by the method described in the joint Australian and New Zealand Standard (AS/NZS 4063:1992), where the individual values are ranked in ascending order, and assigning them rank values, Ri as described by the following equation:

$$Ri = (i - 0.5)/(n) \qquad [6.1]$$

Where: i = 1,2,3..etc. for the first, second, third etc. ranked values;
n = sample size.
The fifth percentile corresponds to Ri = 0.05.

The fifth percentile values of the tensile and compression strengths for the tested timber on the basis of log types, positions relative to the pith, machine and visual grades (4 machine stress and 3 visual grades) and three groups of trees (on the basis of ranking according to stiffness) are presented in Tables 6.6 - 6.10. Also, Figures 6.1 - 6.4 show typical cumulative frequency distribution curves for tensile strength on the basis of log types, positions relative to the pith, machine stress grades and the three groups of trees ranked according to stiffness.

6.2 CHARACTERISTIC STRESS

6.2.1 Definition

According to the New Zealand standard (NZ3603:1993) the characteristic stress or strength (K_R) for strength properties is defined as an estimate of the lower 5-percentile value determined with 75% confidence from tests on a representative sample of full size test specimens. For stiffness the characteristic value (K_E) is the mean value.

The characteristic stresses (K_R) for tensile strength and compression strength for this

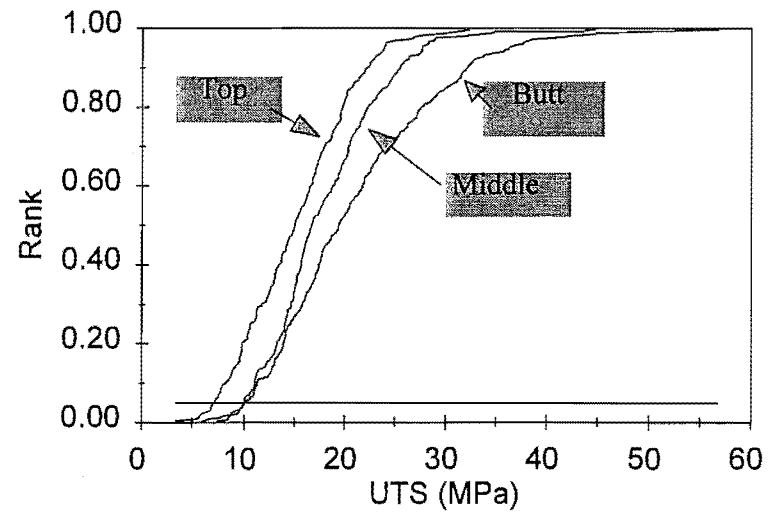


Figure 6.1 **Typical cumulative frequency distribution curves for tensile strength on the basis of log type.**

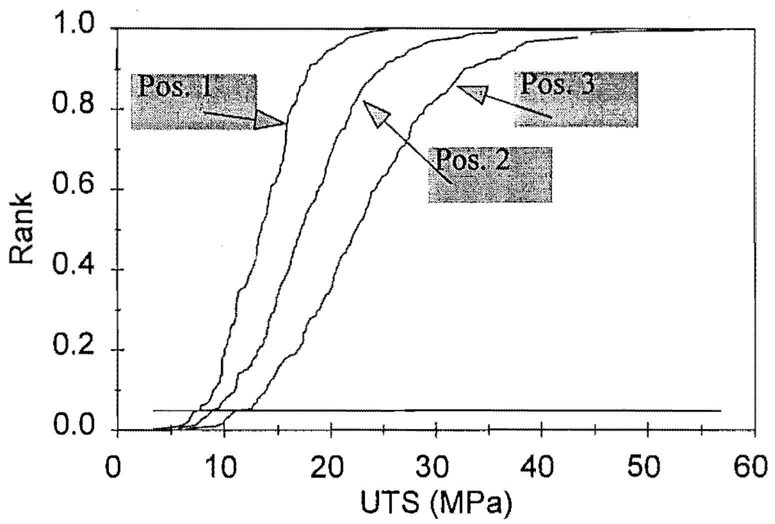


Figure 6. 2 **Typical cumulative frequency distribution curves for tensile strength on the basis of positions relative to the pith.**

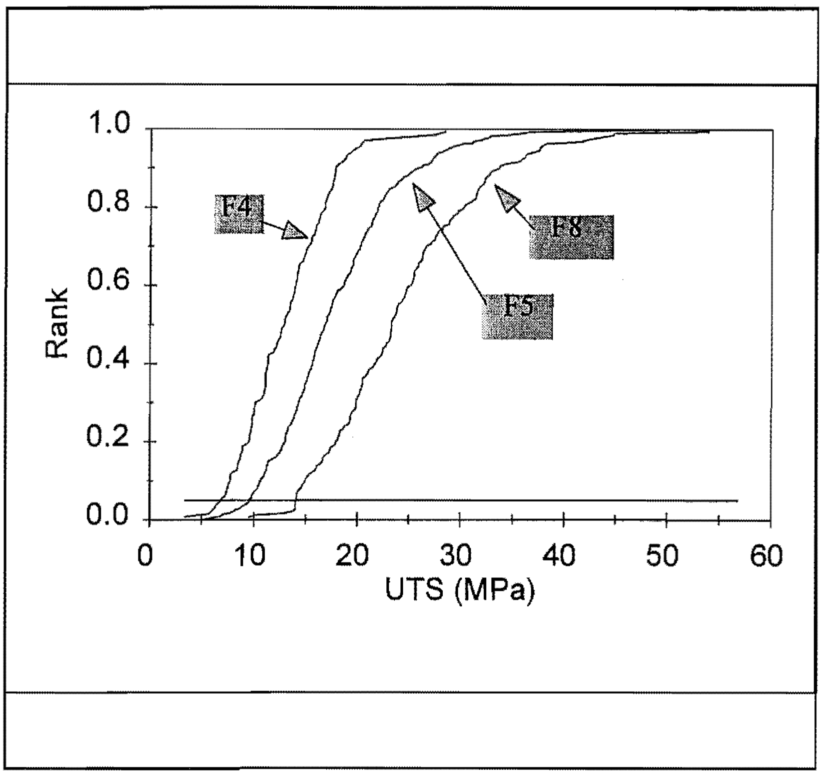


Figure 6.3 **Typical cumulative frequency distribution curves for tensile strength on the basis of MSG.**

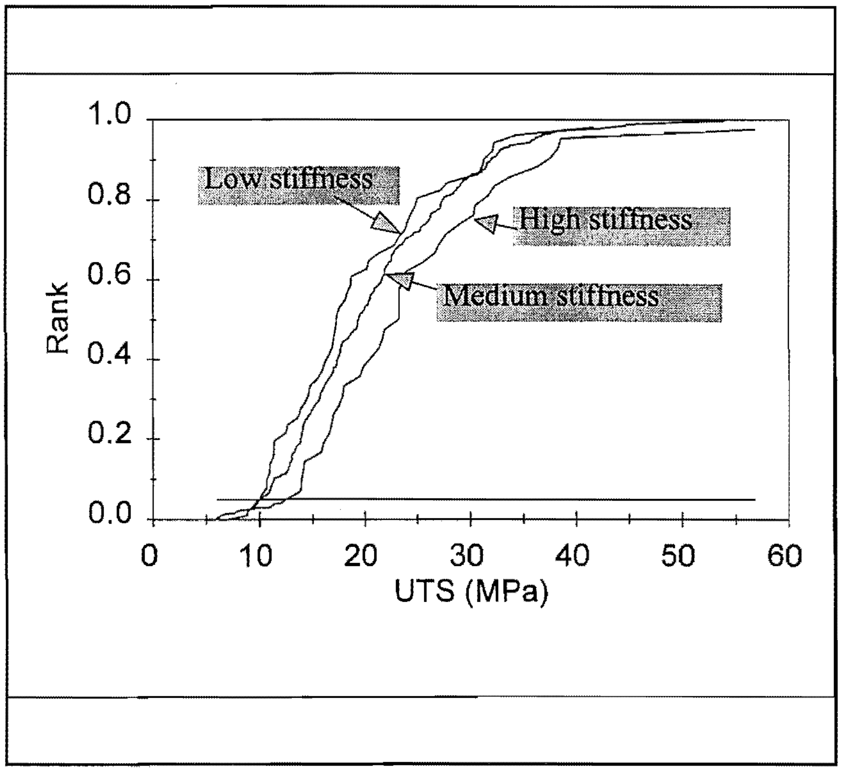


Figure 6.4 **Typical cumulative frequency distribution curves for tensile strength on the basis of the three groups of trees ranked according to stiffness.**

study were estimated from the lower 5-percentile values in accordance with the procedures outlined in the Australian/New Zealand Standard (AS/NZS 4063:1992). The lower 5-percentile is reduced by a factor (F) as follows:

$$F = (1 - 2.7V_R/\sqrt{n}) \qquad [6.2]$$

where: V_R = coefficient of variation of the measured data and
n = sample size.

This adjustment reflects the confidence with which the lower 5-percentile value of a population can be estimated when using a small sample.

6.2.2 **Code values**

6.2.2.1 **Characteristic stress**

The characteristic stress code values of New Zealand, Australia and Europe are presented in Tables 6.1 - 6.3.

Table 6.1 **Summary of the New Zealand design code characteristic stresses for visually graded timber (NZS 3603:1993).**

Grade	Characteristic stresses			
	Bending (MPa)	Compression (MPa)	Tension (MPa)	MOE (GPa)
No.1 Framing	17.7	20.9	10.6	8.0
Engineering	27.7	25.7	16.5	10.5

Table 6.2 **Summary of the Australian design code characteristic stresses for mechanically graded timber (AS 1720-1: 1988 Revision).**

Grade	Characteristic stresses			
	Bending (MPa)	Compression (MPa)	Tension (MPa)	MOE (GPa)
F14	41.3	30.1	21.1	12.0
F11	32.5	24.8	16.6	10.5
F8	25.4	19.5	13.0	9.1
F7	20.4	15.3	10.3	7.9
F5	16.2	12.1	8.2	6.9
F4	12.7	9.7	6.5	6.1
F3	10.0	7.7	5.0	5.2
F2	8.0	6.2	4.0	4.5

Table 6.3 **Summary of the European design code (PREN338, 1993) characteristic stresses for mechanically graded timber: poplar and softwoods species.**

Grade	Characteristic stresses			
	Bending (MPa)	Compression (MPa)	Tension (MPa)	MOE (GPa)
C40	40.0	26.0	24.0	14.0
C35	35.0	25.0	21.0	13.0
C30	30.0	23.0	18.0	12.0
C27	27.0	22.0	16.0	12.0
C24	24.0	21.0	14.0	11.0
C22	22.0	20.0	13.0	10.0
C18	18.0	18.0	11.0	9.0
C16	16.0	17.0	10.0	8.0
C14	14.0	16.0	8.0	7.0

Buchanan (1990) reported that the reason that tensile strength is less than bending strength is mainly due to two size effects:

1. a "length effect", where the bending specimen has high stresses in only the central part of the length, whereas the tension specimen has high stresses over the whole

length;

2. a "depth effect", where at the failure cross section, the bending specimen has high tension stresses only at one edge, whereas the tension specimen has high stresses over the whole cross section.

Some relationship between bending strength and tension strength is expected because most bending failures in commercial quality timber result from fracture in the tension zone. In this study, tests were chosen to be in tension, not bending, in order to test the full length of each board under constant stress.

6.2.2.2 **Ratio of tensile strength to bending strength**

In most countries, characteristic stresses in bending and compression are determined directly from bending and compression tests, respectively. However, for tension, characteristic stresses are usually assumed to be a fixed proportion of the bending value. Traditionally that was a high proportion (80% - 90%) but that proportion has been dropping steadily as more in-grade testing has been carried out. Most codes now have a characteristic tension stress 50% or 60% of the characteristic bending stress.

a. **Ratio of tensile to bending strength for different countries**

The ratio of tensile to bending stresses in design codes for different countries as described by Walford (1982) parallel with the current code values, calculated from Tables 6.1 - 6.3 above are presented in Table 6.4 below.

Table 6.4 **Ratio of tensile to bending stresses for different countries**.

Country	Previous position (Walford, 1982)		Current position (calculated from Tables)	
	Code	Ratio	Code	Ratio
New Zealand	NZS 3603:1981	0.8	NZS 3603:1993	0.6
Australia	AS986: 1970	0.6	AS 1720-1:1988	0.5
U.K/Europe	CP112:1973	0.7	PREN338, 1993	0.6

A ratio of 0.5 for tensile to bending stresses for radiata pine has been obtained by Bolden *et al.* (1994). Addis Tsehaye (1989) obtained a ratio of 0.5 for a boxed-pith timber from Nelson, New Zealand. For the current study the 0.5 ratio will be used to estimate characteristic stress in bending.

b. **Buchanan's equation**

The bending strength of the in-grade timber in this study can also be estimated from the tensile strength using Buchanan's equation.

Buchanan (1989) states:

> "Bending strength depends on three main factors, the ratio of tensile to compressive strength, nonlinear ductile behaviour in the compression zone, and a size-dependent brittle fracture in the tension zone."

The starting point for an ultimate strength theory is a realistic description of stress-strain relationships in axial tension and compression. Typical stress-strain relationships for clearwood are shown in Figure 6.5.

On the basis of the above theory Buchanan (1989) described a model that explains the relationship between the bending strength and the ratio of tensile to compressive strength of wood using four separate modes of failure as follows:

Mode One

For material that has a lower failure stress in tension than the proportional limit in compression, bending failures result from brittle fracture in the tension zone, with no compression yielding. As shown in Figure 6.6 the moment curvature relationship (or load-deflection relationship) is linear to failure.

This behaviour is characteristic of weak pieces of commercial timber.

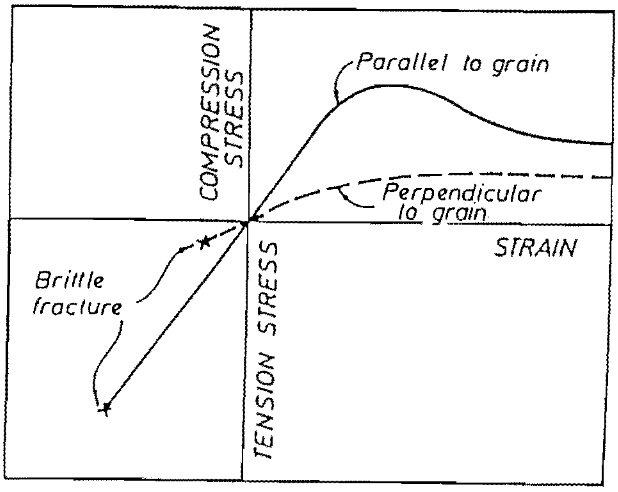


Figure 6.5 **Typical stress-strain relationship for clearwood (from Buchanan, 1989).**

Mode Two

For material with an intermediate ratio of tension to compression strength, the maximum moment is still associated with brittle tensile failure, but after some compressive yielding has occurred. As compression yielding occurs, the neutral axis shifts toward the tension face, and tensile stresses continue to increase until failure occurs as a rupture in the tensile zone (Figure 6.6).

This behaviour occurs with stronger pieces of commercial timber. Bending strength depends on both tensile and compressive strengths of the material.

Mode Three

For material that is considerably stronger in tension than in compression, the ultimate bending strength is governed by compression behaviour alone. As significant compression yielding occurs, the moment reaches a peak and begins to decrease (Figure 6.6), but tension stresses continue to increase until rupture occurs in the tension zone at a moment below peak moment. For a beam loaded by load control (i.e. gravity loading rather than displacement control), failure would occur rapidly once maximum moment was reached.

Small clear specimens of wood generally fail in modes two or three, depending on the ratio of tension to compression strength.

Mode Four

This is the extreme case for material that is very much stronger in tension than in compression, where maximum moment is again associated with compression yielding, but no tension failure occurs (Figure 6.6).

This type of failure will be familiar to anyone who has tried unsuccessfully to snap a green branch on a living tree, finding that a plastic hinge forms but the branch does not break. Moisture content affects the mode of failure, because increasing moisture content causes a much larger reduction in compression than tension strength, leading to an increase in the ratio of tension to compression strength.

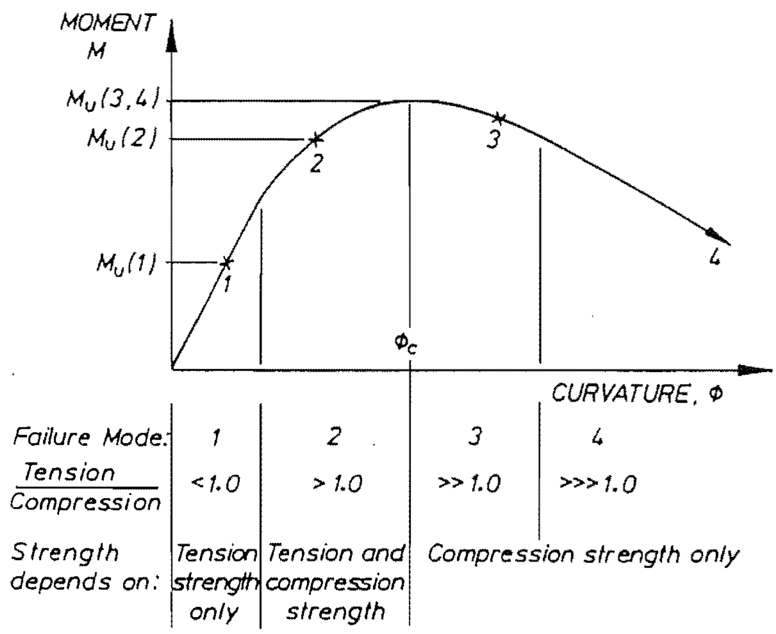


Figure 6.6 **Load-deflection relationship (from Buchanan, 1989)**.

On the basis of the above description the bending strength of the graded timber (Experiment I) should be categorised as "mode one" failure because in-grade tensile strength is less than in-grade compression strength. Hence, the bending strength of this material can be estimated from its tensile strength using the equation described by Buchanan (1989):

$$\log MOR = 1/k\,[\log(k+1) - \log c] + \log UTS \qquad [6.3]$$

where:

MOR = modulus of rupture (MPa)

UTS = maximum tensile strength (MPa)

k = the stress distribution parameter

c = the depth of neutral axis as a ratio depth (d) of the cross-section

Equation (6.3) could be rewritten as:

$$UTS = MOR \times G \qquad [6.4]$$

Where:

$$G = [c/(k + 1)]^{1/k} \qquad [6.5]$$

For a typical value of k = 10.0, and c = 0.5 (neutral axis at the mid-depth) we obtain G = 0.73.

Before estimating the bending strength of the graded timber from its tensile strength the values of tensile strength must be adjusted for the length effect as shown in Equation 6.6 described by the brittle fracture theory (Madsen and Buchanan 1986).

$$\log(X_1/X_2) = 1/k_1[\log(L_2/L_1)] \qquad [6.6]$$

Where X_1 and X_2 are the strength (MPa) of members of length L_1 and L_2 (m), respectively and k_1 is the length effect parameter.

If the 90x35 mm timber was tested in accordance with AS/NZS 4063:1992 the length of the tension specimens would be 2.6 m between grips and the length of the bending specimens would be 1.62 m between supports, with four-point loading. In order to predict the strength in a standard bending test, it is necessary to make a correction for length effect. Madsen and Buchanan (1986) have shown that the effective length of a four point bending specimen is given by:

$$L_e = L(1 + k_1/3)/(1 + k_1) \qquad [6.7]$$

Where, L_e and L are effective length and span length (m) respectively, and k_1 is the length effect parameter.

Madsen and Buchanan (1986) have also shown that the length effect parameter, k_1 can be related to the coefficient of variation (C.V.). This relationship is described by Equation 6.8.

$$C.V. = k_1^{-0.922} \quad [6.8]$$

In theory, the C.V. in equation 6.8 should reflect the variability at various cross sections within each board. Data is not available, but there is data on the variability between boards (C.V. = 0.39), so this will be used.

The estimated bending strength from the tensile strength for the tested timber and the ratio of the measured tensile strength to the estimated bending strength are presented in Table 6.5.

Table 6.5 **The estimated bending strength from tensile strength for all the 915 boards and on the basis of the four positions relative to the pith using Buchanan's equation.**

Property	UTS/MOR (MPa) by positions relative to the pith				All
	1	2	3	4	
(a) Measured UTS	13.5	17.8	23.2	29.1	18.6
(b) Length-adjusted UTS (Equ.6.6)	20.0	26.9	34.7	42.7	27.5
(c) Estimated MOR (Equ. 6.4)	27.4	36.8	47.5	58.5	37.7
Ratio (a/c)	0.49	0.48	0.49	0.50	0.49

It is interesting to note that Buchanan's equation gave a tensile strength to bending strength ratio of about 0.5 for the current timber, similar to those values given in Table 6.4.

6.3 CHARACTERISTIC STRESS FOR THE TESTED TIMBER

6.3.1 Results

A summary of characteristic stresses (K_R), mean, coefficient of variation (V_R) and fifth percentile values for tensile strength and compression strength, and characteristic stresses for stiffness (K_E) is presented in Tables 6.6 - 6.15.

Table 6.6 **Summary of characteristic stresses of tensile strength, compression strength and modulus of elasticity based on log types.**

Log	UTS (MPa)				MCS (MPa)				MOE (GPa)
	Mean	V_R	5%-ile	K_R	Mean	V_R	5%-ile	K_R	Mean
Top	15.2	0.35	7.2	6.7	25.8	0.24	17.5	16.7	6.6
Middle	17.9	0.32	10.0	9.5	26.1	0.22	18.6	17.4	7.0
Butt	20.9	0.40	10.2	9.7	26.5	0.20	19.0	17.6	6.8
All	18.6	0.39	9.0	8.7	26.1	0.22	22.2	21.4	6.8

n/a = not applicable.

Table 6.7 **Summary of characteristic stresses of tensile strength, compression strength and modulus of elasticity based on relative positions from pith.**

Relative position	UTS (MPa)				MCS (MPa)				MOE (GPa)
	Mean	V_R	5%-ile	K_R	Mean	V_R	5%-ile	K_R	Mean
1	13.5	0.28	7.8	7.4	24.1	0.20	17.5	16.4	5.0
2	17.8	0.33	8.9	8.5	25.7	0.21	18.1	17.4	6.7
3	23.2	0.35	11.4	10.7	27.9	0.23	18.7	18.2	8.5
4	29.1	0.33	n/a	n/a	30.7	0.14	n/a	n/a	9.5
All	18.6	0.39	9.0	8.7	26.1	0.22	22.2	21.4	6.8

n/a = not applicable.

Table 6.8 **Summary of characteristic stresses of tensile strength, compression strength and modulus of elasticity based on the three groups of trees: ranking according to stiffness.**

Group of Trees	UTS (MPa)				MCS (MPa)				MOE (GPa)
	Mean	V_R	5%-ile	K_R	Mean	V_R	5%-ile	K_R	Mean
LS	12.1	0.28	10.0	8.9	24.8	0.30	17.0	15.7	4.7
MS	20.2	0.13	10.2	10.0	25.9	0.32	17.8	16.1	6.5
HS	25.7	0.04	12.5	12.3	27.8	0.34	19.5	17.7	8.4

LS = low stiffness; MS = medium stiffness; HS = high stiffness.

Table 6.9 **Summary of characteristic stresses of tensile strength, compression strength and modulus of elasticity based on machine stress grades.**

MSG	UTS (MPa)				MCS (MPa)				MOE (GPa)
	Mean	V_R	5%-ile	K_R	Mean	V_R	5%-ile	K_R	Mean
F4	13.1	0.33	6.8	6.6	21.6	0.19	16.8	19.1	4.8
F5	17.8	0.35	9.6	9.6	25.0	0.18	18.6	21.9	6.6
F8	24.2	0.31	14.0	13.3	31.1	0.17	23.3	26.8	8.7
F11	34.6	0.29	n/a	n/a	34.5	0.09	n/a	n/a	10.6
All	18.6	0.39	9.0	8.7	26.1	0.22	22.2	21.4	6.8

Table 6.10 **Summary of characteristic stresses of tensile strength and modulus of elasticity based on visual grades.**

Visual grade	UTS (MPa)				MOE (GPa)
	Mean	V_R	5%-ile	K_R	Mean
Box	11.6	0.34	6.8	6.4	5.6
No.2F	15.3	0.22	11.2	10.7	6.3
No.1F	22.5	0.30	14.0	13.5	7.5
All	18.6	0.39	9.0	8.7	6.8

The characteristic bending stresses of the machine stress grades estimated from the characteristic tensile stresses of the test data are presented in Table 6.11 below.

Table 6.11 **Summary of characteristic bending stresses estimated from characteristic tensile stresses of the tested timber based on machine stress grades.**

Grade	N	Characteristic stresses		
		Tension (MPa)	Bending (MPa)	MOE (GPa)
F4	132	6.6	13.2	4.8
F5	593	9.6	19.2	6.6
F8	179	13.3	26.6	8.7
F11	11	n/a	n/a	10.6
All	915	8.7	17.4	6.8

n/a = not applicable.

Tables 6.12 and 6.13 show summaries of the comparison of characteristic values in tension and stiffness for the tested timber with the code values. The tables do not include comparisons for compression and bending properties, these properties and a comparison based on the three groups of trees (ranked according to stiffness) will be covered later in the discussion.

Table 6.12 **Comparison of the characteristic values in tension and stiffness with the code values based on log types and relative positions from pith.**

Log/pos.	New Zealand		Australia		Europe	
	Strength	Stiffness	Strength	Stiffness	Strength	Stiffness
Top log	-	-	F4	F4	-	-
Mid. Log	-	-	F5	F5	C14	C14
Butt log	-	-	F5	F4	C14	-
Pos. 1	-	-	F4	F2	-	-
Pos. 2	-	-	F5	F4	C14	-
Pos. 3	No.1F	No.1F	F7	F7	C16	C16
Pos. 4	n/a	Engin.	n/a	F8	n/a	C22

- = below code value; n/a = not applicable because of small sample size.

Table 6.13 **Comparison of the characteristic values in tension and stiffness with the code values based on machine stress and visual grades.**

Grade	New Zealand		Australia		Europe	
	Strength	Stiffness	Strength	Stiffness	Strength	Stiffness
F4	-	-	F3	F2	-	-
F5	-	-	F5	F4	C18	-
F8	No.1F	-	F8	F7	C22	C16
F11	n/a	Engin.	n/a	F11	n/a	C22
Box	-	-	F4	F3	-	-
NO.2	No.1F	-	F7	F3	C16	-
NO.1	No.1F	-	F8	F5	C22	C14

- = below code value; n/a = not applicable because of small sample size.

6.3.2 **Discussion**

6.3.2.1 **Results by log and positions relative to the pith, all grades combined**

The results in Table 4.16 show that boards from the top logs for tensile strength and stiffness and boards from the butt logs for stiffness satisfy the equivalent code values for the Australian F4 grade in tensile strength and stiffness. Boards from the butt logs in tensile strength and middle logs in tensile strength and in stiffness satisfy the equivalent code values for the Australian F5 grade. Boards from the middle logs for tensile strength and stiffness and the butt logs for tensile strength satisfy the equivalent code value for European C14 grade.

In the case of the results of the effect of positions relative to the pith (Table 4.16), boards from position 1 satisfy the equivalent code values for the Australian F4 grade for tensile strength and F2 grade in stiffness. Boards from position 2 satisfy the equivalent code values for he Australian F5 grade and European C14 grade for tensile strength and Australian F4 grade in stiffness. The boards from position 3 satisfy the equivalent code values for the Australian F7, the European C16 and the New Zealand No.1 Framing grades for tensile strength and stiffness while boards from position 4 satisfy the equivalent code values for the Australian F8, the European C22 and the New Zealand Engineering grades in stiffness.

Concerning the compression parallel to the grain (Table 6.6), the boards from all the three types of logs satisfy the equivalent code values for the Australian F8 grade, while boards from the top logs, middle logs and butt logs satisfy the equivalent code values for European C16, C18 and C22 grades respectively. Boards from the middle and butt logs also satisfy the equivalent code values for the New Zealand No.1 Framing grade in compression parallel to the grain. The results in Table 6.6 show that all the boards from the four positions relative to the pith satisfy the equivalent code values for the Australian F8 grade in compression parallel to the grain. Comparison with the European code values shows that boards from position 1 satisfy the equivalent code values for C21 grade while boards from positions 1 and 3 satisfy for C22 grade.

Note, when all the logs, positions relative to the pith and grades combined (i.e.

average values for all samples Tables 6.6 and 6.7), satisfy the equivalent code values for the Australian F5 and European C14 grades for tensile strength, the Australian F8 and European C24 grades in compression, but only the Australian F4 grade in stiffness.

The values for the three groups of trees ranked according to stiffness (Table 6.8) could also be compared with the code values (Tables 6.1 - 6.3). The characteristic stress values for the five low stiffness trees satisfy the code values for the Australian F3 and European C14 grades for tensile strength, the Australian F7 and European C18 grades in compression parallel to the grain and only the Australian F2 grade in stiffness. The values for the medium stiffness trees satisfy the equivalent code values for the Australian F4 and European C16 grades for tensile strength, the Australian F8 and European C18 grades in compression and the Australian F4 in stiffness. The values for the five high stiffness trees satisfy the equivalent code values for the Australian F7, European C18 and New Zealand No.1 Framing grades for tensile strength, the Australian F8, European C24 and New Zealand No.1 Framing grades in compression and the Australian F7, the European C16 and New Zealand No.1 Framing grades in stiffness.

6.3.2.2 **Results by grade, all logs and relative positions from pith combined**

Comparing the test results for the machine stress grades (Table 6.13) with given code values, it can be seen that the values for the F11 machine stress grade are equivalent to the code values for the Australian F11, the European C22 and the New Zealand Engineering grades in stiffness. The results for the F8 machine stress grades satisfy the equivalent code values for the Australian F8, the European C22 and the New Zealand No.1 Framing grades for tensile strength, the Australian F11 grade and above the European and New Zealand code values in compression, but only the Australian F7 and European C16 grades in stiffness.

The F5 machine stress grades satisfy the equivalent code values for the Australian F5 and European C18 grades for tensile strength, the Australian F8 and European C27 and New Zealand No.1 Framing grades in compression, but only equivalent to the code values for the Australian F4 grade and below the European and New Zealand code values in stiffness. The F4 machine stress grade is only equivalent to the Australian F3 grade for tensile strength, F2 grade in stiffness, the Australian F8 and European C22 grades in compression parallel to the grain.

In the case of the test data for the visual grades (Table 6.10), the results for the No.1 Framing grade satisfy the code values for the Australian F8 and European C22 and New Zealand No.1 Framing grades for tensile strength and the Australian F5 and European C14 grades and in stiffness. The results for No.2 Framing grades satisfy the equivalent code values for the Australian F7, European C16 and New Zealand No.1 Framing grades for tensile strength, but only the Australian F3 grade in stiffness. The results for the box grade satisfy only the code values for the Australian F4 grade for tensile strength and F3 grade in stiffness.

The estimated bending strength values (Table 6.11) can also be compared with the corresponding code values of bending strength for each grade in Tables 6.1 - 6.3. The estimated bending strength values of the F8 machine stress grade satisfy the equivalent code values for the Australian F8, European C24 and New Zealand No.1 Framing grades for bending strength. The F5 machine stress grades satisfy the equivalent code values for the Australian F5 and European C18 grades for bending strength. The F4 machine stress grades satisfy the equivalent code values for only the Australian F4 grade for bending strength.

Finally, the derived bending strength values for all the 915 boards (all grades combined) satisfy for the equivalent code values of the Australian F5 and European C16 grades for bending strength.

6.4 **STRESS GRADE**

A stress grade is defined by the Australian/New Zealand Standard (AS/NZS 4063:1992) as "a population of timber that has been grouped for structural purposes".

According to AS/NZS 4063:1992, in addition to the derivation of characteristic stress values for each structural property, it may be desirable to classify a timber into a stress grade. In order to classify the reference population into stress grades that are denoted by F-grades in AS 1720.1:1988, preliminary classifications are first made for each of the individual properties. On the basis of these preliminary classifications, the final classification for the reference population of sawn timber is given as shown in Table 6.14.

Table 6.14 **Reference population F-grade classification for sawn timber (AS/NZS 4063:1992)**

Preliminary classification			Resultant stress grade for reference population
Bending strength	Tension strength	Modulus of elasticity	
F	F	F	F
F	F+1	F-1	F
F	F-1	F+2	F
F-1	F+1	F+2	F

Notes: F= notation for stress grade.
F-grade F+1 is one grade higher than F-grade F.

Using the above procedure the grade recovery of the tested timber based on the machine stress grades (Table 6.11) is summarised in Table 6.15 below.

Table 6.15 **Summary of F-grade classification for the tested timber**

MSG	N	Preliminary classification (compared to code values)			Resultant stress grade for reference population	
		Bending* strength	Tension strength	Modulus of elasticity	Grade	Proportion (%)
F4	132	F4	F3	F2	F2	14.6
F5	593	F5	F5	F4	F4	65.6
F8	179	F8	F8	F7	F7	19.8
F11	11	n/a	n/a	F11	n/a	n/a

n/a = not applicable because of small sample size; MOR is derived from UTS.

In Table 6.15 above the grade proportion (%) was calculated for only the 904 boards (i.e. leaving out the eleven F11 boards). It can be seen that all the machine stress grades satisfy their respective F-grades in bending strength and tensile strength (except F4 in tensile strength). However, none of the machine stress grades satisfy the respective code value with regard to stiffness, hence the resultant stress grades are lowered by a single grade (F-1) in the case of machine stress grades F8 and F5, and by two grades (F-2) in the case of F4.

6.5 REASSESSMENT OF GRADES ON THE BASES OF DIRECT STIFFNESS MEASUREMENTS

The results discussed above (Sections 6.3 and 6.4) show that none of the machine stress grades fulfill the code values for the respective Australian grades with regard to stiffness. This grade outcome necessitated a reassessment of grades using the direct stiffness measurement obtained during proof testing, by bending over a span of 3.3 m, as described in Section 3.4.4.1.

The reassessment procedure involved assigning a "F-grade" to each board on the basis of its measured modulus of elasticity, using the Australian Standards values (AS1720.1-1988) as shown in Table 6.2, as cut-off values.

A summary of the grade outturn for the 915 boards from the direct measurement of stiffness together with their other experimentally determined characteristics of tensile strength and density is presented in Table 6.16.

Table 6.16. **Summary of machine stress grades, with mean modulus of elasticity (MOE), ultimate tensile strength (UTS) and density based on the machine grades: grading on the basis of direct, long span stiffness measurement (AS1720.1-1988).**

GRADE in Stiffness	N	MOE (GPa)	UTS (MPa)	Density (kg/cu.m)
<F2	88	3.9 (0.4)	13.0 (3.9)	473 (42.6)
F2	99	4.8 (0.2)	14.2 (4.0)	475 (52.0)
F3	160	5.6 (0.3)	15.7 (5.1)	462 (36.8)
F4	136	6.4 (0.2)	17.5 (5.9)	469 (43.9)
F5	153	7.4 (0.3)	19.2 (6.1)	467 (37.1)
F7	166	8.4 (0.4)	21.8 (6.0)	481 (35.5)
F8	90	9.6 (0.4)	26.3 (8.7)	503 (42.1)
F11	23	11.9 (0.4)	27.2 (12.1)	495 (65.0)
Total	915	6.8 (1.9)	18.6 (7.3)	475 (43.1)

Value in parenthesis is a standard deviation.

Table 6.17 compares the grade outturn of the material by the stress grading machine together with that for the "true" grades above (Table 6.16) on the basis of direct stiffness measurement.

Table 6.17 **A comparison of the grade outturn from the machine stress grade (MSG) with that of the grades from direct stiffness measurement.**

MSG	Grades from direct stiffness measurements								Total
	<F2	F2	F3	F4	F5	F7	F8	F11	
F4	64	31	23	3	5	5	-	1	132
F5	22	67	133	129	125	82	27	8	593
F8	2	1	4	4	22	79	58	9	179
F11	-	-	-	-	-	-	6	5	11
Total	88	99	160	136	152	166	91	23	915

Value in parenthesis is the number of boards.

Table 6.17 shows that of the 11 boards graded as "F11", 179 boards graded as "F8", 593 boards graded as "F5" and 132 boards graded as "F4" only 45%, 32%, 21% and 2% respectively of these boards exceed the Australian code values in stiffness for the respective grades. Even allowing for the fact that MSG only requires the mean stiffness of the sub population making a particular grade to have a stiffness at least as great as that required for that grade. This suggests that the variation in the grade outturn was due at least in part to "over grading" by the grading machine.

Assigning grades to the 915 boards using direct stiffness measurement gave a grade distribution of 23 boards F11, 91 boards F8, 166 boards F7, 152 boards F5 and 483 boards F4 and below. This procedure is conservative and would understate the grade outturn for a correctly calibrated machine stress grade.

6.6 STRATEGIES FOR ELIMINATING LOW GRADE MATERIAL

In the previous discussion (Section 6.3) it was shown that all the 915 boards (i.e. all three log types and all positions within logs combined) give a mean stiffness and 5th percentile tensile strength values of 6.8 GPa and 9.0 MPa respectively. There is an interest to improve value recovery of structural material for radiata pine. This can be done by eliminating low grade material from the rest of the sawmills production. It was shown earlier (Chapter 4) that there is more low stiffness and weaker timber in positions 1 and 2 and more high stiffness and stronger timber in positions 3 and 4. The reason for this was that the two positions near the pith (positions 1 and 2) contain pith and pith-associated material.

In this section alternative strategies are used to improve both the mean stiffness and the 5th percentile strength values. The criteria used as "cut off points" to eliminate low grade material from the rest of the population are as follows:

1. Removal of material from near the pith - using board location as a tool:
   (a) positions relative to the pith; or
   (b) nominal distance (mm) from the pith.
2. Removal of low stiffness material; and
3. Removal of material with large knots (visual grading).

The values for the modulus of elasticity and tensile strength were ranked using each of the above criterion and their "cut off points" determined. A "cut off point" in this section means a value below which any value of the modulus of elasticity or tensile strength is eliminated in the analysis of the mean or 5th percentile value.

6.6.1 **Results**

The results of the analysis on the basis of the above three criteria are summarised in Tables 6.18 - 6.21.

Table 6.18 **Summary of 5%-ile values and characteristic stresses of tensile strength and mean modulus of elasticity, and equivalent grades (AS 1720-1: 1988) using position relative to the pith as a cut off point.**

Boards assessed (Positions)	N	UTS (MPa)					MOE (GPa)	
		Mean	V_R	5%-ile	K_R	Grade	Mean	Grade
All boards	915	18.6	0.39	9.0	8.7	F5	6.8	F4
2+3+4	709	20.0	0.37	9.9	9.5	F5	7.4	F5
3+4	269	23.7	0.34	12.6	11.9	F7	8.5	F7

Position = position relative to the pith; N = number of boards.

Table 6.19 **Summary of 5%-ile values and characteristic stresses of tensile strength and mean modulus of elasticity, and equivalent grades (AS 1720-1: 1988) using distance (mm) from the pith as a cut off point.**

Cut off Distance (mm)	N	UTS (MPa)					MOE (GPa)	
		Mean	V_R	5%-ile	K_R	Grade	Mean	Grade
All boards	915	18.6	0.39	9.0	8.7	F5	6.8	F4
20	893	18.7	0.39	9.2	8.9	F5	6.9	F5
30	777	19.5	0.37	9.6	9.3	F5	7.2	F5
40	678	20.3	0.36	9.9	9.5	F5	7.5	F5
50	543	21.2	0.36	10.5	10.1	F5	7.8	F5
60	392	22.8	0.34	11.3	10.8	F7	8.2	F7

N = number of boards.

Table 6.20 **Summary of 5%-ile values and characteristic stresses of tensile strength and mean modulus of elasticity, and equivalent grades (AS 1720-1: 1988) using modulus of elasticity as a cut off point.**

Cut off MOE (GPa)	N	UTS (MPa)					MOE (GPa)	
		Mean	V_R	5%-ile	K_R	Grade	Mean	Grade
All boards	915	18.6	0.39	9.0	8.7	F5	6.8	F4
3.5	905	18.6	0.38	9.2	8.9	F5	6.9	F5
4.5	825	19.2	0.38	9.6	9.3	F5	7.2	F5
5.5	676	20.2	0.36	9.9	9.5	F5	7.6	F5
6.5	489	21.7	0.35	11.2	10.7	F7	8.3	F7
7.5	345	22.9	0.34	12.6	12.0	F7	8.8	F7

N = number of boards.

Table 6.21 **Summary of 5%-ile values and characteristic stresses of tensile strength and mean modulus of elasticity, and equivalent grades (NZS 3603: 1993) using visual grade as a cut off point.**

Boards assessed, Visual grades	N	UTS (MPa)					MOE (GPa)	
		Mean	V_R	5%-ile	K_R	Grade	Mean	Grade
All boards	915	18.6	0.39	9.0	8.7	-	6.8	-
No.2F+No.1F	721	20.4	0.33	12.5	9.3	-	7.2	-
No.1F	513	22.5	0.30	14.0	13.5	No.1F	7.5	-

N = number of boards; - = below code values

6.6.2 **Discussion**

Tables 6.18 - 6.21 show comparative results in terms of grade improvement. The decision in the choice of the above strategies should be made by the sawmiller. However, the points to be considered include easies of operation, less proportion of reject material and most importantly the financial benefit that could be achieved by eliminating low grade material.

First compare the improvements in both the 5th percentile tensile strength and mean stiffness values using positions relative to the pith (Table 8.18) and distance (mm) from the pith (Table 6.19). By eliminating all "position 1" material (i.e. all pith-containing material) from the population, both the 5th percentile tensile strength and mean stiffness values improve only by 9%, whereas by eliminating material below 50 mm distance from the pith (i.e. all pith-associated material), the 5th percentile and mean stiffness values improve by 16% and 15% respectively.

In terms of improving stiffness (i.e. the outturn of machine stress grades), any one of the alternative strategies shown in Tables 6.18 - 6.20 can be used. However, the important decision in this case should be upgrading of "reject" material (F4 and below) to F5 by elimination only few boards. For example, compare modulus of elasticity (Table 6.20) with that of distance from the pith (Table 6.19). When using the modulus of elasticity, by eliminating only 10 least stiff boards (i.e. <3.5 GPa) the whole mill production can be upgraded by one grade in stiffness whereas in using distance 22 boards adjacent to the pith (i.e. within 20 mm distance from the pith) must be eliminated to upgrade the material to the same grade. The stiffness of a board can be easily determined using some sort of *in situ* stiffness measuring device at the sawmill or using the stress grading machine.

The use of visual grading (Table 6.21) is a strategy that gives a choice between stiffness and strength. If strength is preferred, knots can be used as a criterion for eliminating weak material without much effect in the number of boards. It can be seen from Table 6.21 that by eliminating No.2F and below boards with knots occupying more than half of the cross-section (NZS 3631: 1988), the 5th percentile of tensile strength can be improved greatly (56%) while the improvement in the mean stiffness is modest (10%).

CHAPTER 7: **BASIC WORKING STRESS**

As used in design codes, the "working stress" is the safe stress that a piece of wood can be subjected to under expected long term loads.

In order to compare the results of this study directly with those of the previous studies (Addis Tsehaye, 1989; Hadi, 1992, Smith *et al.*, 1993; Walford, 1994; Bolden *et al.*, 1994) it has been necessary to compute the basic working stress (BWS) values according to the methods used both by Bier (1984) and the Australian/New Zealand Standard (AS/NZS 4063:1992). As there is a difference in BWS values derived using the two methods, it will be important to the examine this difference as well.

7.1 **DERIVATION OF BWS USING AS/NZS 4063:1992 versus BIER (1984)**

In the method described by Bier (1984) basic working stresses were calculated by multiplying the lower 5-percentile values by a factor of 0.45 for bending, tension and shear strength properties and 0.60 for compression strength. This means that in the previous method the only important factor was the magnitude of the lower 5-percentile values.

In the current method (AS/NZS 4063) the lower 5-percentile value is first reduced by a factor, F as described in equation 6.2 earlier. This adjustment reflects the confidence with which the 5-percentile value of a population can be estimated using a small sample. This value is in turn reduced further by 1.75 to allow for the duration of load and by $(1.30+0.7V_R)$ which is deemed to be the true factor of safety. Thus the basic working stress (BWS) is given by:

$$BWS = \{R0.o5(1 - 2.7V_R/\sqrt{n})\}/\{1.75(1.30+0.7V_R)\} \qquad [7.1]$$

The above equation shows that the multiplying factors are affected not only by the values of the lower 5-percentile, but also by the values for the coefficient of variation (V_R) of the measured data and sample size. Figure 7.1 shows the effect of the coefficient of variation and sample size on the multiplying factor. It can be seen from Figure 7.1 that a multiplying factor of 0.44 can only be achieved if the coefficient of variation (V_R) was zero which is approximately equivalent to the 0.45 multiplying factor in the method described by Bier (1984). This indicates that the BWS values derived using the current method will be much lower than previously applied. Figure 7.1 also shows that as the V_R decreases the values of the multiplying factor for various sample sizes converge to the same point. It also indicates that the effect of sample size decreases as the sample size increases.

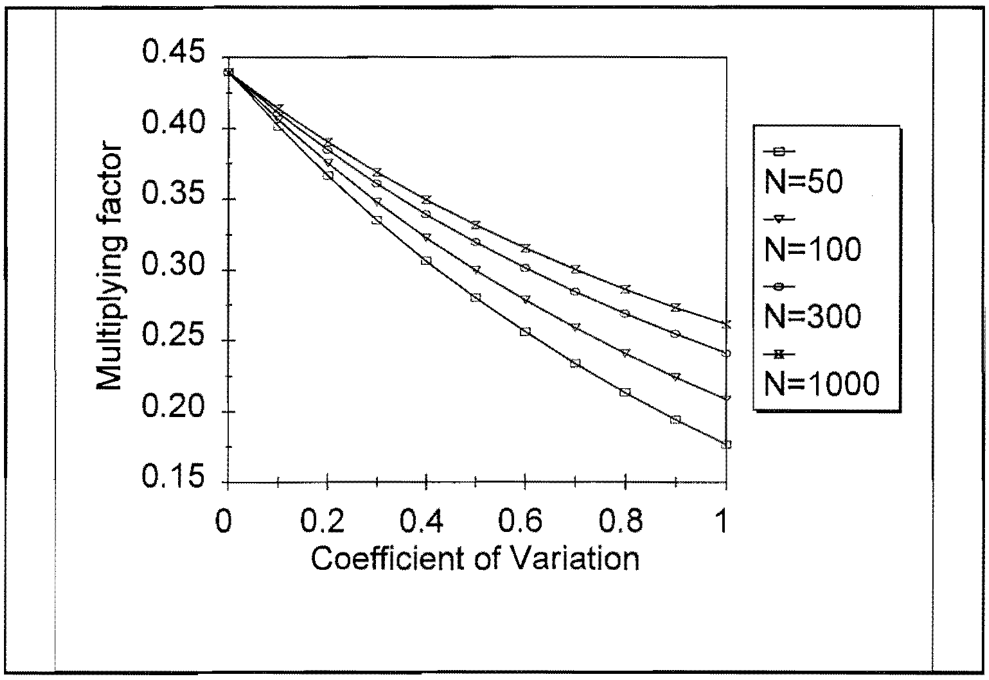


Figure 7.1 **Multiplying factor versus coefficient of variation for various sample sizes.**

7.1.1 **Basic working stresses of the tested timber**

The basic working stresses (BWS) of the test data on the basis of machine and visual grades, calculated using both the new (AS/NZS 4063) and old (Bier, 1984) methods are presented in Tables 7.1 and 7.2.

Table 7.1 **Summary of basic working stresses of tensile strength, compression strength and modulus of elasticity based on machine stress grades.**

MSG	Basic Working stress				MOE (GPa)
	UTS (MPa)		MCS (MPa)		
	New	Old	New	Old	
F4	2.7	3.1	5.3	10.1	4.8
F5	3.8	4.3	6.1	11.2	6.6
F8	5.2	6.3	7.4	14.0	8.7
All	3.2	4.1	5.8	10.9	6.8

Note: New = AS/NZS 4063; Old = Bier (1984).

Table 7.2 **Summary of basic working stresses of tensile strength and modulus of elasticity based on visual grades.**

Visual grade	Basic Working stress		MOE (GPa)
	UTS (MPa)		
	New	Old	
Box	2.4	3.1	5.6
No.2F	4.2	5.0	6.3
No.1F	5.1	6.3	7.5
All	3.2	4.1	6.8

Note: New = AS/NZS 4063; Old = Bier (1984).

7.1.2 **Discussion**

As expected the values in Tables 7.1 and 7.2 show that the basic working stress values calculated according to the procedures described in the Australian/New Zealand Standard (AS/NZS 4063:1992) are lower than those values calculated using the procedures of Bier (1984). Thus, basic working stress values for tensile strength are lowered by 15 - 20% and for compression strength by 30 - 70%. Currently there is no need to calculate the basic working stresses as the new limit states design (LSD) principle in the New Zealand Standard (NZS 3603:1993) and in the newly revised version of the Australian Standard (AS 1720.1:1988) is in operation. The advantage of the LSD principle is that design is based on the actual strength of the material so that test results can be used directly in the design process. The soft conversion factor from characteristic stress to basic working stress is 2.95 for bending strength and compression strength and 2.0 for tensile strength.

7.2 COMPARISON WITH PREVIOUS STUDIES

The results of the current study can be directly compared with those of previous studies on full-sized members of radiata pine. The previous studies selected for comparison include work by Bier (1984), Addis Tsehaye (1989), Hadi (1992), Smith *et al.* (1993), Walford (1994) and Bolden *et al.* (1994).

7.2.1 Grade recovery

Walford (1994) on his study of 90x45 mm timber sawn from a 25-year-old stand in Kaingaroa Forest, New Zealand, calculated grade recovery using boards sawn only from upper logs (i.e. 2nd, 3rd, 4th and 5th logs, excluding boards from the butt logs) and compared his results with those of Bier (1984) who tested 90x45 mm timber sawn from 28-year-old radiata pine stand and Whitside (1974) who calculated grade recovery from a 50-60-year-old radiata pine stand both from Kaingaroa Forest. The machine grade recovery in the current study using only 516 boards sawn from the middle log and top log (Table 4.2) to make the results more directly comparable to those of Walford (1994). These are presented in Table 7.3.

Table 7.3 **Machine stress grade recovery of the current study compared with the results of Walford (1994).**

Source	Age	Machine stress grade (%)			
		F8	F5	F4	Reject
Whiteside (1974)	50+	36	28	11	25
Bier (1984)	28	16	36	18	30
Walford (1994)	25	1	25	37	37
Current study					
Baigents' grades	25	20	65	14	-
'True grades' (Table 6.17)	25	10	35*	15	38

* = 166 (18%) boards graded as F7 are added to the 152 (17%) F5 boards.
'True grades' = grades assigned on the basis of direct stiffness measurement.

As expected Table 7.3 shows that the recovery percentage of higher grades decreases and that of lower grades increases with decreasing stand age. The better outturn (20%) of F8 grade in the current study is surprising. However, the case is overstated for the following reasons:

First, when we compare the original machine stress grade outturn with that of the 'true grade', it was indicated earlier (Chapter 6) that the stress grading machine had over-graded the material. Note that in Table 7.3 above the other authors did not grade for F7, if they did some of their F5 would have been F7. Hence in order to make a fairer comparison the 18% F7 (Table 6.17) is put as F5.

The second reason could be attributed to the more limited number of upper logs. Only the 2nd and 3rd upper logs were used which gave a higher proportion of better quality outerwood compared with those of the comparative studies used by Walford (1994). However, such a reason would be wrong as small trees with a higher corewood-to-outerwood proportion were used in the current study compared with those used by Walford.

Third, the absence of reject material in the current study was simply due to the objective of the test programme not the nature of the material itself. There was no need physically to segregate boards which were distorted after drying as the objective was destructively to test the boards in tension.

7.2.2 **The mean and lower 5-percentile values**

The mean and lower 5-percentile values of the current study can be compared with the results of Walford (1994) who studied 90x45 mm timber in short and long lengths (i.e. for short lengths 1850 mm in tension and 1150 mm in compression, and for lengths 2950 mm in tension and 2050 mm in compression), from a 25-year-old plantation in Kaingaroa Forest, New Zealand and with that of Addis Tsehaye (1989) who studied 90x45 mm boxed-pith radiata pine timber in 3 different lengths from a normal mill run from the Nelson Region, New Zealand.

The mean and 5-percentile values of New Zealand timber could also be compared with that of Smith *et al.* (1993) who studied 95x45, 145x45 and 195x45 mm radiata pine timber from normal mill runs collected from different regions of Chile. Only the values for the 95x45 mm specimens are selected for comparison.

Comparison of the current results with the results of Walford (two different length specimens), Addis Tsehaye (only for the 3.9 m length specimens in tension and stiffness) and Smith *et al.* (1993) are presented in Table 7.4.

Table 7.4 **Summary of mean and 5-percentile values of the current study parallel with those of Walford (1994), Smith et al. (1993) and Addis Tsehaye (1989).**

Source	Tension (MPa)			Compression (MPa)			MOE (GPa)
	Mean	V_R	5%-ile	Mean	V_R	5%-ile	
Walford (Kaingaroa)							
Short specimen	17.1 (298)	0.60	6.4	25.9 (319)	0.30	15.2	6.2 (262)
Long specimen	12.1 (298)	0.58	3.8	22.1 (319)	0.25	13.2	6.5 (262)
Addis Tsehaye (Boxed-pith, Nelson)	14.1 (208)	0.17	12.0	23.5 (72)	0.26	17.0	6.4 (208)
Current study (Whole tree, Canterbury)	18.6 (915)	0.39	9.0	26.1 (286)	0.22	18.1	6.8 (915)
Smith (Chile)	20.4 (297)	0.57	8.5	25.7 (254)	0.24	17.2	8.3 (297)

Figures in parenthesis are number of samples.

Table 7.4 shows that the mean values of tensile strength and modulus of elasticity of the current study are higher than those recorded by Walford (1994). It may be argued that the material for the current study was a 'mill run' with all boards from logs i.e. no good ones taken out for appearance grades, while in Walford's case all the boards from the butt logs were segregated for such purposes. However, this reason alone cannot account for the differences observed, especially in the case of the long specimens in tension. Table 7.4 also shows that the mean values of tensile strength and modulus of elasticity of the Chilean timber are higher than those of the New Zealand timber. In the case of compression strength the current study shows the highest value. This result could be misleading for the reason explained earlier that in the current study compression specimens were cut from boards already tested in tension which means that the worst defect had already been removed during the tension test. In general, it can be said that the New Zealand radiata pine is no less than that of radiata pine from Chile in compression strength.

7.2.3 **Basic working stress**

The basic working stress values of the current study can be directly compared with the results of Walford (1994) who calculated basic working stress values for his short specimens on the basis of visual grades and with the results of Bolden *et al.* (1994) who calculated on the basis of machine stress grades on his study of 90x35 mm radiata pine timber taken from various mills throughout Australia. Both workers calculated basic working stress values according to AS/NZS 4063: 1992.

The basic working stress values of the current study which parallel the results of Walford (1994) and Bolden *et al.* (1994) are presented in Tables 7.5 and 7.6.

Table 7.5 **Summary of basic working stress values of the current study parallel with those of Walford (1994) on the basis of visual grades.**

Source	Visual Grade	Basic Working stress			
		Bending (MPa)	Tension (MPa)	Comp. (MPa)	MOE (GPa)
Walford (1994)	Box	2.6	3.8	5.0	4.3
(Kaingaroa)	No.2F	3.9	4.6	7.1	5.8
	No.1F	5.5	5.2	7.6	6.0
Current	Box	n/a	2.4	n/a	5.6
study	No.2F	n/a	4.2	n/a	6.3
(Canterbury)	No.1F	n/a	5.1	n/a	7.5

n/a = not available

Table 7.6 **Summary of basic working stress values of the current study parallel with those of Bolden et al. (1994) on the basis of machine stress grades.**

Source	MSG	Basic Working stress		
		Tension (MPa)	Comp. (MPa)	MOE (GPa)
Bolden (1994)	F5	3.0	8.0	10.0
(Australia)	F8	5.1	9.8	12.7
	F11	7.7	12.0	15.2
Current*	F5	4.3	8.8	6.6
study	F8	6.3	10.8	8.7
(N.Z)	F11	n/a	n/a	10.6

* = Baigents machine stress grades.
n/a = not available.

Finally, the boxed-pith material of the current study (i.e. boards cut adjacent to the pith, which are represented by position 1, Tables 4.7 and 4.8) can be directly compared with the results of Addis Tsehaye (1989) and with that of Hadi (1992) who tested 90x45 mm boxed-pith timber cut from the butt logs of 7-year-old radiata pine thinnings from Canterbury Forests.

A summary of results of the boxed-pith timber of the current study parallel with the results of Addis Tsehaye (1989) and Hadi (1992) are presented in Table 7.7.

Table 7.7. **Summary of mean, 5-percentile and basic working stress values of the current study compared with those of Addis Tsehaye (1989) and Hadi (1992).**

Source	N	Tension (MPa)			MOE (GPa)
		Mean	5%-ile	BWS*	
Addis Tsehaye (1989) (Nelson, all boxed-pith)	623	14.1	12.0	5.4	6.4
Current study (Canterbury, all boxed-pith, Table, 4.9)	206	13.5	7.8	3.5	4.9
Hadi (1992) (Canterbury, boxed-pith from butt logs only)	222	10.7	6.7	3.0	2.9
Current study (Canterbury, boxed-pith from butt logs only, Table 4.12)	83	14.2	9.4	4.2	4.5

* = basic working stress calculated according to the method of Bier (1984).

7.2.4 **Discussion**

When comparing the basic working stress values of the current study with those of Walford (1994) on the basis of visual grades (Table 7.5) a conclusion could be drawn that there is not much difference in the tensile strength of radiata pine from Kaingaroa Forest and that from Canterbury Plains. However, concerning the modulus of elasticity, radiata pine from the Canterbury Plains Forests shows a better value for all visual grades.

The observations in both Tables 7.4 and 7.5 are surprising in that this timber from the Canterbury Plains has similar mechanical properties to similarly aged wood from Kaingaroa Forest selected as representative of future wood supply (Walford, 1994). This is a significant finding because older trees from Kaingaroa forest have been the traditional bench mark for New Zealand timber. The Nelson boxed-pith timber (Addis Tsehaye, 1989) has comparable properties, and one might deduce that the outerwood quality for Nelson timber would be much superior to that studied here. A re-evaluation of regional variations of wood properties may be needed as the age of plantation forests readjusts to the clear felling of older stands and the age of clear felling settles at between 25 and 30 years. The general approach in wood quality studies has been to differentiate between regions on the basis of wood density. It is possible that this has obscured the fact that mechanical properties do not appear to be so largely affected. Values for radiata pine reported by Walford (1994) and Canterbury University (Addis Tsehaye, 1989; Hadi, 1992 and this study) are systematically lower than representative values (i.e. for small clear specimens 20x20 mm) noted in a recent technical appraisal (Kininmonth and Whitehouse, 1991) and fall short of properties for commercially important species of the Northern Hemisphere (Walford, 1991).

It is also interesting to note that radiata pine from New Zealand exhibits a lower stiffness compared with those of Chile (Table 7.4) and Australia (Table 7.6). Radiata pine from Chile is 22 - 34% stiffer compared with the values recorded both in this study and in Walford (1994). Comparing the results of the current study with that of Australia on a grade-by-grade basis, it is seen that radiata pine from Australia is stiffer by 52%, 46% and 43% for machine stress grades F5, F8 and F11 respectively.

The results for boxed-pith timber in the butt log (Table 7.7) are comparable to, but somewhat greater, than the results of Hadi (1992) who examined 90x45 mm boxed-pith boards from a notionally similar stand on the Canterbury Plains. He found mean values of 2.9 GPa and 10.7 MPa for the modulus of elasticity and tensile strength respectively compared with 4.5 GPa and 14.2 MPa in this study. This difference may be due to the fact that with Hadi (1992) the boxed-pith timber was cut with a scragg-saw which held the pith exactly in the central position at both ends of the log so the boxed-pith timber has less semi-mature wood. The present finding again confirms that boxed-pith radiata pine from the Canterbury Plains is inferior (by about 31%) in stiffness compared with boxed-pith material from the Nelson Region in New Zealand (Addis Tsehaye, 1989).

PART II: RESULTS AND DISCUSSION OF EXPERIMENT TWO (CLEARWOOD SPECIMENS)

Chapter 8: RESULTS AND DISCUSSION OF EXPERIMENT II: TESTS ON CLEARWOOD SPECIMENS

8.1 TEST SPECIMENS

This chapter describes the results of tests on small clear specimens tested in bending and compression. Tensile testing of clearwood has not been considered in this project because it is extremely difficult to execute. In contrast to Experiment I where in-grade timber is tested in tension, in Experiment II the clearwood from the Experiment I specimens were tested in bending and in compression. The procedures for the preparation of clearwood specimens has been discussed earlier in Chapter 3. Two clearwood bending samples were obtained from each in-grade board to give 1830 samples. Compression samples were taken only from those boards categorised as being of either high or low stiffness.

Further material came from the short internodal top log (which was cut from above the top log). The small end diameter (sed) was too small to yield any sawn timber but could provide small clearwood specimens, extending the range of data on clearwood properties. 320 samples were cut from the 48 trees. A summary of tests and number of specimens is shown in Table 8.1.

Table 8.1 **Summary of tests, number of matching specimens and sample size.**

Mode of testing	Source of material	Number of specimens per board or log	Number of boards or logs	Total number of specimens
Bending	Boards tested in tension	2	915	1830
Compression parallel to the grain	Boards tested in tension	2	207	414
Bending	Short internodal top logs	6 to 7	48	320
Total		-	-	2564

8.2 WITHIN-TREE VARIATIONS

8.2.1 Vertical variations

In the previous experiment (Experiment I) the vertical variations were examined using three log types (i.e. butt, middle and top logs), whereas in this experiment a further short internodal top log was included. The four types of logs discussed are butt log, middle log, top log and internodal top log. The vertical variations in the mean modulus of elasticity, bending strength and density were examined on the basis of these four types of logs, while the analysis on compression parallel to the grain was only on the basis of the three log types (i.e. butt, middle, and top logs).

8.2.1.1 Modulus of elasticity, bending strength and density

All values for bending strength, modulus of elasticity and density are presented in Appendix 2A. The mean modulus of elasticity (MOE), modulus of rupture (MOR) and density for all specimens, sorted on the basis of log type are presented in Table 8.2. Also shown is the percentage change in moving from the log below (from butt log → middle log → top log → internodal top log).

Table 8.2 **Mean values of modulus of elasticity (MOE), modulus of rupture (MOR) and density based on the four log types.**

Log type	N	MOE (GPa)	Change (%)	MOR (MPa)	Change (%)	Density (kg/cu.m)	Change (%)
Internodal top log	320	7.5 (1.8)	-3.0	59.8 (9.7)	-9.3	445 (40.4)	-2.6
Top log	442	7.7 (1.5)	-7.0	64.4 (9.6)	-3.0	457 (32.7)	-0.9
Middle log	590	8.3 (1.7)	-7.8	66.4 (11.4)	-2.4	461 (34.2)	-5.1
Butt log	798	7.7 (2.1)	-	68.1 (13.2)	-	486 (41.3)	-
Total	2150	7.8 (1.8)		65.6 (11.9)		467 (40.6)	

Value in parenthesis is a standard deviation.

Table 8.2 shows that the mean modulus of elasticity is high for the middle log, and the reason for such a high value is unknown. It can be seen from Table 8.2 that there is a drop of 3% in the mean modulus of elasticity from the butt log to the internodal top log, while the bending strength and density drop by 12% and 8% respectively.

An analysis of variance test was performed to determine the potentially significant differences between the stiffness and bending strength values of each log type. The results of the analysis of variance test are summarised in Tables 8.3 and 8.4.

Table 8.3 **Difference comparison between mean modulus of elasticity (MOE) values of the four log types.**

MOE (GPa)	Log type	Internodal top log	Top log	Middle log	Butt log
7.5	Internodal top log	-	ns	**	ns
7.7	Top log	ns	-	**	ns
8.3	Middle log	**	**	-	*
7.7	Butt log	ns	ns	*	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant.

Table 8.4 **Difference comparison between mean bending strength (MOR) values of the four log types.**

MOR (MPa)	Log type	Internodal top log	Top log	Middle log	Butt log
59.8	Internodal top log	-	**	**	**
64.4	Top log	**	-	**	**
66.4	Middle log	**	**	-	**
68.1	Butt log	**	**	**	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Tables 8.3 and 8.4 show that there is a significant difference between the logs in terms of bending strength, but not so much difference in terms of modulus of elasticity.

8.2.1.2 **Compression strength**

A total of four hundred and fourteen 60 mm long, 20x20 mm specimens were used for the compression test. Specimens for compression testing were taken only from boards coming from the five highest and five lowest stiffness trees as determined in Experiment I.

All the values of maximum crushing strength (MCS) are presented in Appendix 2B. The mean maximum crushing strength values sorted on the basis of the three log types are summarised in Table 8.5. Also shown is the percentage change in moving from the log below (from butt log → middle log → top log).

Table 8.5 **Mean values of compression strength (MCS) based on the three log types.**

Log	N	MCS (MPa)	Change (%)	Density (kg/cu.m)	Change (%)
Top log	102	31.1 (4.8)	-4.9	475 (36.4)	-0.4
Middle log	130	32.7 (5.5)	-1.2	477 (40.3)	-8.4
Butt log	182	33.1 (5.8)	-	517 (48.3)	-
All	414	32.5 (6.0)		494 (47.4)	

Value in parenthesis is a standard deviation.

Table 8.5 shows that the drop in the mean compression strength in moving from the butt log to the top log is 6.0% while that in the mean density is 8.1%.

An analysis of variance test was performed to determine the potentially significant differences between the mean compression strength values of each log type. The results of the analysis of variance test are summarised in Table 8.6.

Table 8.6 **Difference comparison between mean compression strength (MCS) values of the three log types.**

MCS (MPa)	Log type	Top log	Middle log	Butt log
31.1	Top log	-	**	**
32.7	Middle log	**	-	*
33.1	Butt log	**	*	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns= not significant

Table 8.6 shows that the top log is significantly different from both logs at 1% significant level, while differences between the butt log and the middle log are only significant at 5% level.

8.2.1.3 **Discussion**

The vertical variations in the mean bending strength (Table 8.2) and compression strength (Table 8.5) could be compared with the results of Langlands (1938) who examined changes on the same properties in clearwood (20x20 mm) specimens sawn from a 33-year-old radiata pine tree in Australia. He divided the height of the tree into 2.4 m sections using the lowest 2.4 m section as a reference. He made a comparative analysis of changes in bending and compressive strength up the height of the tree. His results showed that bending strength was reduced by 2 - 5% in moving from the 2.4 m section to the 4.8 m section, by 5% in moving from the 2.4 m to the 7.2 m section, and by 10% in moving from the 2.4 m section to the 9.6 m section up the height of the tree. For compressive strength he observed a much higher overall reduction of 19 - 22% up the tree.

The rates of change in the mean bending strength values for the 25-year-old radiata pine trees reported in this study are similar to the results obtained by Langlands (1938). The average distance between the mid height of the butt log and the mid height of the internodal top log is approximately 10.0 m. The overall 12% reduction (Table 8.2) in the mean bending strength between the butt log is with the same magnitude with that of the 10% changes between the 2.4 m and 9.6 m sections (i.e. 7.2 m apart) reported by Langlands.

The overall change in the mean compressive strength of 6.4% observed in this study (Table 8.2), however, is almost three times lower than the 19 - 22% reported by Langlands.

The 9% density variation between the butt log and the top log is within the 7% to 11% range reported by Cown *et al.* (1991a) for basic density of radiata pine. Cown and McConchie (1983) in their study of basic density on 10 trees of 12-year-old radiata pine from Kaingaroa Forest reported a drop in the mean density of 20 kg/cu.m between the butt and 3-metre height up the stem followed by a decrease of about 10 kg/cu.m for each 3-metre height to the apex. The density range between the butt log and the middle log and between the top log and the internodal top log (i.e. 25 kg/cu.m and 12 kg/cu.m respectively at a height difference of about 4.1 m) observed in this study is similar with that reported by Cown and McConchie. However, the 4 kg/cu.m difference between the middle log and top log is a little less than they found.

8.2.2 **Radial variation**

Radial variations of the physical and mechanical properties within a stem will be broken into two parts. In the first section radial variations in modulus of elasticity, bending strength, compression strength and density measured in clearwood specimens (cut from the graded boards) will be examined on the basis of the four positions (positions 1 - 4) relative to the pith. In the second section radial variations in the same properties measured in clearwood specimens (cut from the short internodal top logs) will be examined on specimens centred on four growth rings (rings 1, 5, 10 and 15 from the pith).

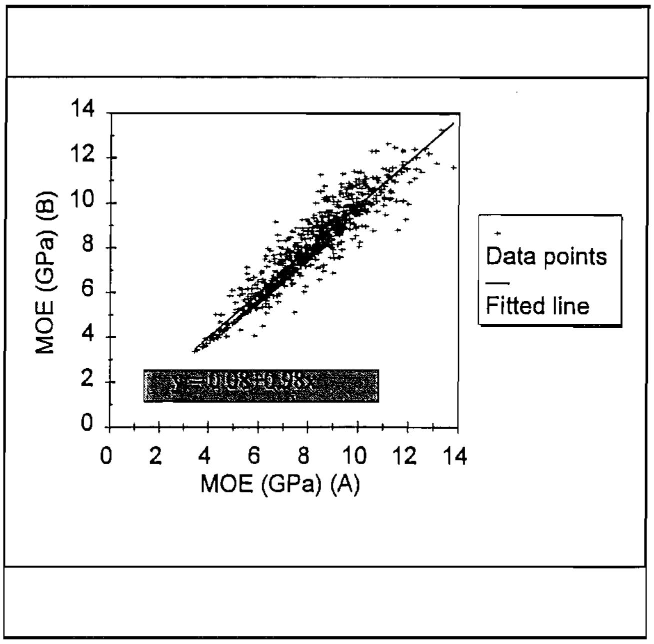
8.2.2.1 **Within-board variations**

Before examining the within-stem radial variations the within-board variations in modulus of elasticity, bending strength and density are compared using values for pairs of clearwood specimens cut from each of the 915 boards which had been tested in tension. Each member of the pair was cut from the same location along the length of the board. The relationships between each pair of values of stiffness, bending strength and density are presented in Figures 8.1a - c. Each pair consists of two specimens A and B cut from the same cross-section of each piece of timber. The allocation into group A and B is random. A linear regression analysis for clearwood pairs of 915 data points showed a very strong relationship (R^2 = 0.88 for modulus of elasticity, R^2 = 0.93 for bending strength and R^2 = 0.98 for density).

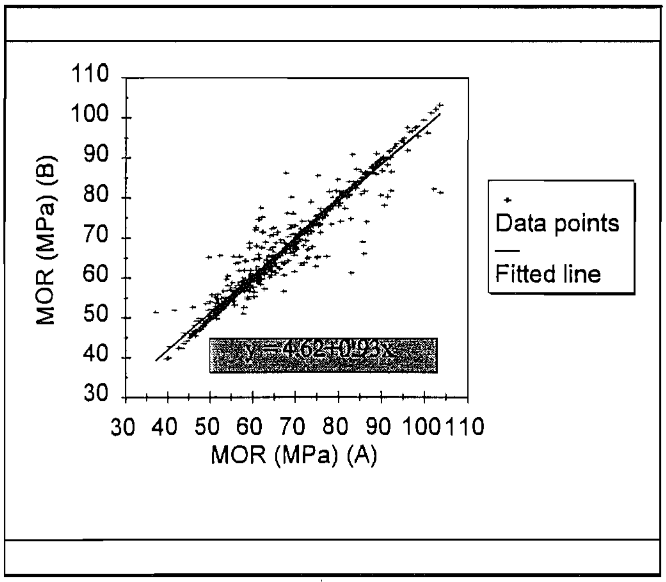
The values of the coefficient of determination (R^2) could be used as an indicator of the variability of each property over the cross-section of a 90x35 mm piece of timber. The weaker the relationships between each pair of data points (for two matching specimens) for a particular property, the lower the value of R^2, and the more will be its variation over the cross-section. Thus, the modulus of elasticity varies more over each cross-section than does bending strength or density.

8.2.2.2 **Positions relative to the pith**

a)



b)



c)

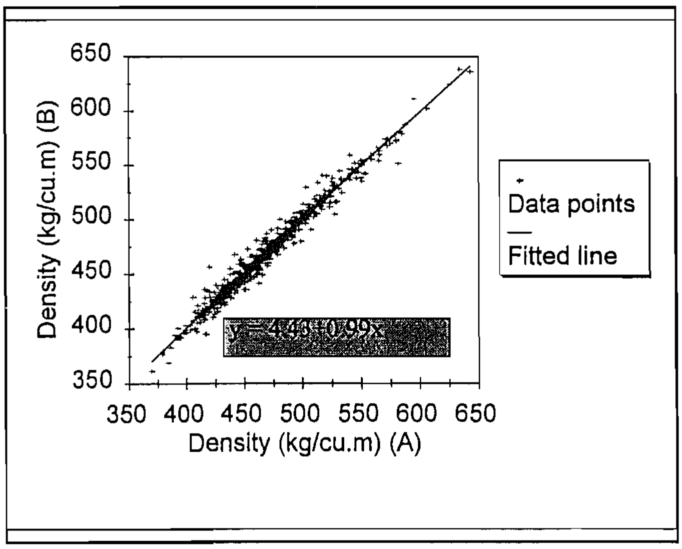


Figure 8.1 Comparison of (a) stiffness, (b) bending strength and (c) density of matched pairs from the same board.

a. **Modulus of elasticity, bending strength and density**

The mean values of the modulus of elasticity (MOE), bending strength and density based on positions relative to the pith, and the changes (%) in moving from one position to the next (from position 1 → position 2 → position 3 → position 4) are shown in Table 8.7.

Table 8.7 **Mean values for modulus of elasticity (MOE), modulus of rupture (MOR) and density for clearwood samples based on positions relative to the pith, all log types aggregated.**

Position	N	MOE (GPa)	Change (%)	MOR (MPa)	Change (%)	Density (kg/cu.m)	Change (%)
1	412	6.1 (1.2)	-	56.3 (7.3)	-	455 (38.1)	-
2	880	7.8 (1.3)	+28.9	64.5 (8.9)	+14.6	465 (33.4)	+2.2
3	500	9.5 (1.4)	+21.8	77.3 (9.3)	+19.8	490 (40.6)	+5.4
4	38	10.2 (1.5)	+7.4	86.3 (12.0)	+11.6	521 (33.7)	+6.3
Total	1830	7.8 (1.8)		66.6 (11.9)		471 (39.4)	

Value in parenthesis is a standard deviation.

Table 8.4 shows that there is a uniform trend of variation in modulus of elasticity, bending strength and density on moving from one position to the next. The overall increases between the position adjacent to the pith (position 1) and that near the cambium (position 4) are 67% in modulus of elasticity, 53% in bending strength and 15% in density.

To determine potentially significant differences between the mean modulus of elasticity and bending strength values of each position relative to the pith an analysis of variance test was performed. The results of the analysis of variance test are shown in Tables 8.8 and 8.9.

Table 8.8 **Difference comparison between mean modulus of elasticity (MOE) values of the four positions relative to the pith.**

MOE (GPa)	Position relative to the pith	Position 1	Position 2	Position 3	Position 4
6.1	Position 1	-	**	**	**
7.8	Position 2	**	-	**	**
9.5	Position 3	**	**	-	**
10.2	Position 4	**	**	*	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Table 8.9 **Difference comparison between mean bending strength (MOR) values of the four positions relative to the pith.**

MOR (MPa)	Position relative to the pith	Position 1	Position 2	Position 3	Position 4
56.3	Position 1	-	**	**	**
64.5	Position 2	**	-	**	**
77.3	Position 3	**	**	-	**
86.3	Position 4	**	**	*	-

*= significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Tables 8.7 and 8.8 show that almost all the differences between each position are significant at 1% significant level.

The increase in the mean density from 455 kg/cu.m at the pith to 521 kg/cu.m at the cambium (i.e. an overall increase of about 15%) is lower than the 30 - 40% increase in the first 20 to 30 growth layers from the pith reported by Cown *et al.* (1991a) for basic density of radiata pine grown in the North Island of New Zealand. However, the changes are comparable with the basic density changes reported by Cown and McConchie (1983) for radiata pine grown in Canterbury and Southland in New Zealand (Figure 8.2). Figure 8.2 clearly shows that in moving from the pith to around growth ring number 15 from the pith, basic density increases from about 340 kg/cu.m to 400 kg/cu.m (i.e. about 18% increase).

Table 8.10 shows the same values presented in Table 8.7 for modulus of elasticity and bending strength at each position relative to the pith, but segregated according to log type. This variation in the mean values of modulus of elasticity and bending strength within a tree is also presented in Figure 8.3.

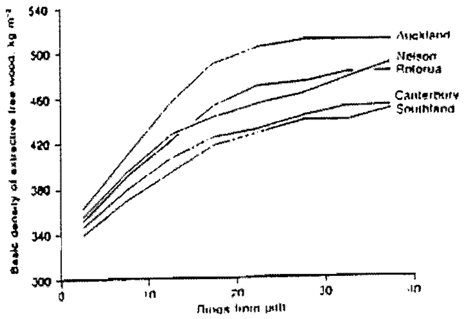


Figure 8.2. **Radial variation in basic density of radiata pine from various localities (from Cown and McConchie, 1983).**

Table 8.10 **Mean values of modulus of elasticity (MOE) and modulus of rupture (MOR) based on positions relative to the pith, segregated according to log type.**

Log type	Position relative to the pith	N	MOE (GPa)	MOR (MPa)
Top	1	116	6.4 (1.1)	57.6 (6.9)
Middle	1	130	6.6 (0.9)	55.9 (7.3)
Butt	1	166	5.5 (1.2)	55.8 (7.4)
Top	2	242	7.9 (1.1)	64.7 (8.4)
Middle	2	288	8.1 (1.2)	64.4 (8.9)
Butt	2	350	7.4 (1.4)	64.5 (9.0)
Top	3	84	9.1 (1.2)	72.9 (8.6)
Middle	3	168	9.9 (1.2)	77.7 (7.1)
Butt	3	248	9.3 (1.5)	78.5 (10.1)
Middle	4	4	10.5	80.0
Butt	4	34	10.1 (1.5)	88.6 (10.5)
All		1830	7.9 (1.8)	66.6 (11.9)

Values in parentheses are standard deviations.

Table 8.10 and Figure 8.3 show that both the modulus of elasticity and bending strength vary over the cross-section and up the height of the stem.

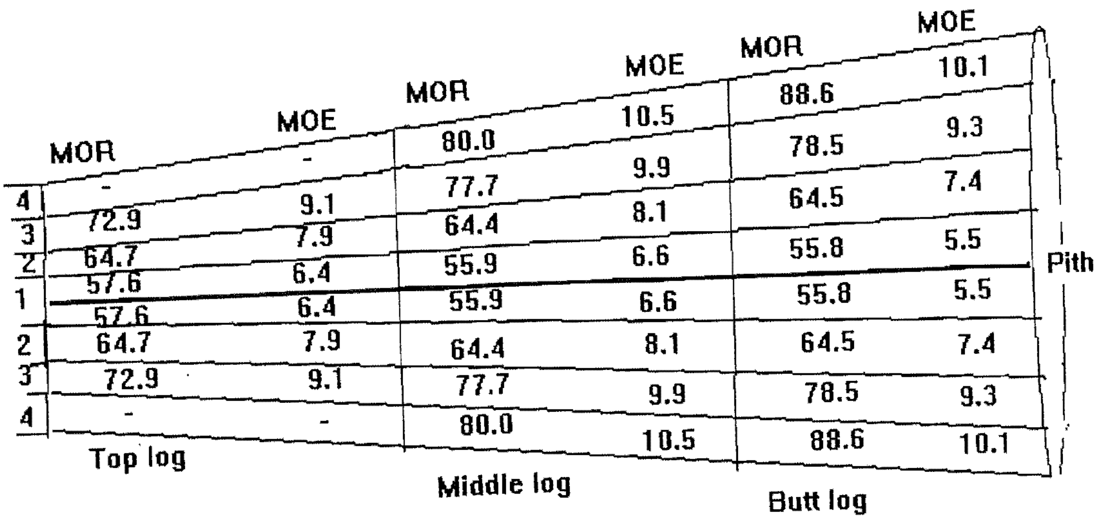


Figure 8.3 **Within-tree variation of modulus of elasticity and bending strength.**

b. **Compression strength**

A summary of results of the mean compression strength and density values based on positions relative to the pith and the changes (%) in the mean values in moving from one position to the next (from position 1 → position 2 → position 3 → position 4) are presented in Table 8.11.

Table 8.11 **Mean values of maximum crushing strength (MCS) and density based on the four positions relative to the pith.**

Position relative to the pith	N	MCS (MPa)	Change (%)	Density (kg/cu.m)	Change (%)
1	82	26.6 (3.4)	-	471 (39.0)	-
2	194	31.2 (4.1)	17.3	482 (42.9)	2.3
3	124	37.5 (5.3)	20.2	523 (41.8)	6.4
4	14	40.2 (2.7)	7.2	524 (43.9)	0.2
All	414			494 (47.4)	

Value in parenthesis is a standard deviation.

Table 8.11 shows that here is an increase in compression strength in moving from one position to the next. The overall increase in moving from position adjacent to the pith (position 1) to that near the cambium (position 4) is 51%.

An analysis of variance was performed to determine the significance of differences between the mean compressive strength values at each position relative to the pith. The results of the analysis of variance test are summarised in Table 8.12.

Table 8.12 **Difference comparison between mean compression strength (MCS) values of the four positions relative to the pith.**

MCS (MPa)	Position relative to the pith	Position 1	Position 2	Position 3	Position 4
26.6	Position 1	-	**	**	**
31.2	Position 2	**	-	**	**
37.5	Position 3	**	**	-	*
40.2	Position 4	**	**	*	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Table 8.12 shows that almost all differences are significant at 1% significant level.

The changes between each position in the mean values of compression strength (Table 8.11) can be directly compared with those in bending strength (Table 8.7). A 51% overall change in the mean compression strength between wood adjacent to the pith (position 1) and near the cambium (position 4) is similar with the 53% increase in bending strength. Again, the between-position variations changes in compression strength, especially, of positions 1 and 2 (17%) and 2 and 3 (20%) are comparable with the 15% and 20% changes between the respective positions in bending strength. However, the 7% increase between positions 3 and 4 in compression strength is less than the 12% increase between the respective positions in bending strength. From the results observed here a general conclusion could be drawn that the trend of radial changes in bending strength are similar with those in compression parallel to the grain strength, which is not surprising as will be shown later.

8.2.2.3 **Successive growth rings from the pith (from internodal top logs)**

The objectives of the research on the internodal top logs were:

a. To prepare specimens on the basis of ring numbers (i.e. rings number 1, 5 10 and 15) from pith so that a comparison of mechanical and physical properties obtained from these specimens could be made with the values obtained from specimens prepared on the basis of relative positions (Section 7.2.2.2); and

b. To identify, physically segregate and analyse the physical and mechanical properties of compression wood, opposite side wood and normal wood separately. This part of the objective will be examined later in Chapter 10.

The values for the modulus of elasticity (MOE), bending strength and density from the three hundred and twenty clearwood (20x20 mm) specimens, cut from the short internodal top logs are presented in Appendix 2C.

A summary of the mean modulus of elasticity, bending strength and density sorted on the basis of the four ring numbers from the pith (rings 1, 5, 10 and 15) and the changes (%) in each property in moving from one ring to the next (rings 1 → 5 → 10 → 15) is presented in Table 8.13.

Table 8.13 **Mean values of modulus of elasticity (MOE), modulus of rupture (MOR) and density based on ring numbers from the pith: specimens from the 48 short internodal top logs.**

Growth ring	N	MOE (GPa)	Change (%)	MOR (MPa)	Change (%)	Density (kg/cu.m)	Change (%)
1	53	4.9 (0.8)	-	47.3 (5.8)	-	417 (47.0)	-
5	76	6.8 (0.9)	+38.8	55.5 (5.1)	17.3	433 (26.9)	+3.8
10	189	8.5 (1.3)	+25.0	64.8 (7.8)	16.8	457 (29.6)	+5.5
15	2	10.0	-	75.6	-	471	-
Total	320	7.5 (1.8)		59.8 (10.8)		445 (40.4)	

Value in parenthesis is a standard deviation.

As expected Table 8.13 shows that all the mean values for the modulus of elasticity, bending strength and density increase with increasing growth ring number away from the pith.

The overall increase between the values for growth rings 1 and 10 are 70% in modulus of elasticity, 40% in bending strength, but only 10% in density.

In growth ring 1 the coefficient of variation for density (Table 8.13) is high (C.V = 11.3%) compared with those for growth ring 5 (C.V = 6.2%) and growth ring 10 (C.V = 6.5%). The relationship between mean density and successive growth rings from the pith is plotted in Figure 8.4a which should be compared to the traditional plot between density and growth ring for radiata pine (Figure 8.2). In our Canterbury wood the initial slope, between rings 1 and 5, is not as steep as expected.

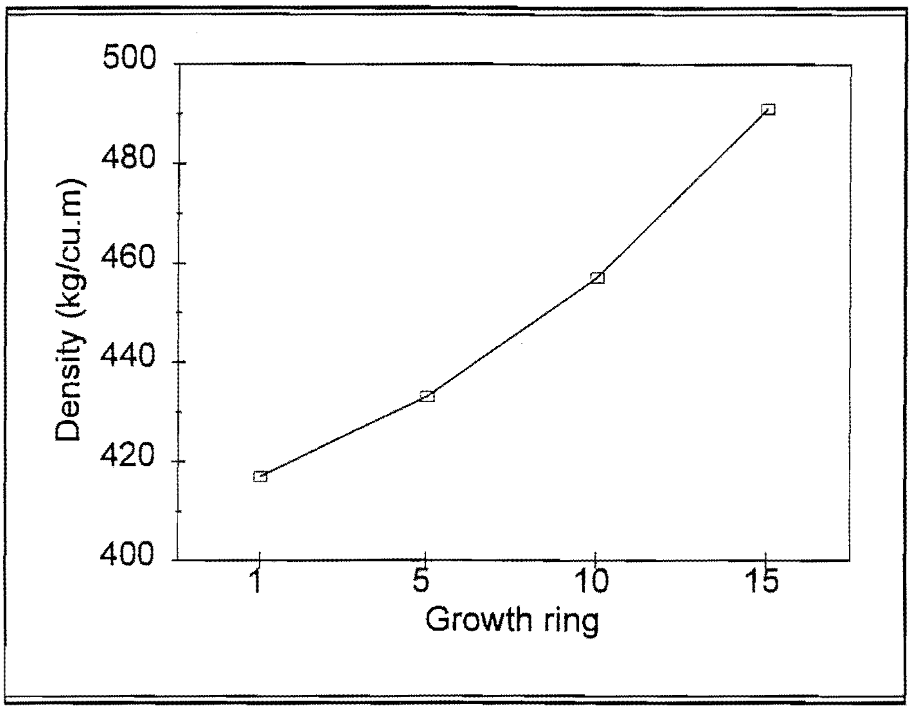
It was observed that the density at growth ring 1 was enhanced by resin infiltration in some clearwood specimens: Of the 53 clearwood specimens from growth ring 1, 12 specimens (23%) were observed to be severely discoloured with dark colour indicating a high resin content. The average density for these 12 samples was 494 kg/cu.m. If these samples are removed from the analysis - on the basis of being strongly atypical, the mean density for ring 1 of the remaining 41 samples decreased to 396 kg/cu.m, with a standard deviation of 24.4 kg/cu.m (C.V = 6.2%). The relationship between density and growth rings using the recalculated mean value (i.e. 396 kg/cu.m) for growth ring 1 is shown in Figure 8.4b.

Causes for atypical resin deposition

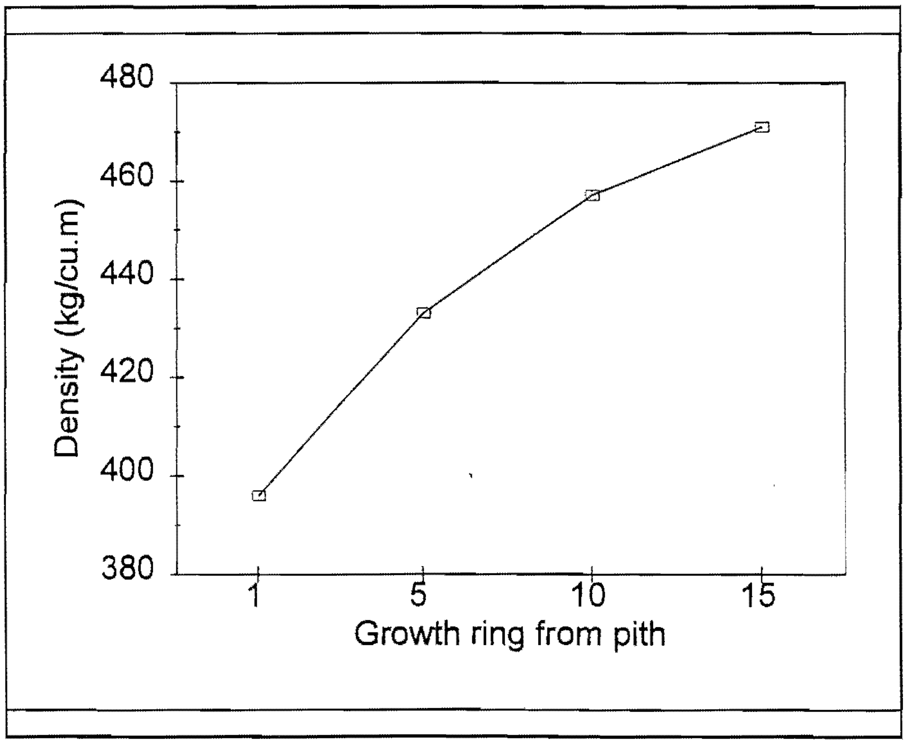
The heavy resin deposits in the 12 samples might have occurred as a result of heavy wind on the trees. For this a record of abnormal wind had to be sought.

The last recorded abnormal wind in the Canterbury Region was the gale of August 1, 1975 which was described by Wilson (1976) as follows:

> "A cold front passed quickly north-east wards over the South Island early on 1 August, 1975. The front was proceeded by north-westerly winds of gale force, stronger than any at Christchurch International Airport since recordings commenced there in 1919. The maximum gust of 170 km/h (92 knots) was recorded at 7.25 a.m and was followed by another of 169 km/h at 8.10 a.m."



a)



b)

Figure 8.4 Density versus growth rings from the pith (a) before removal and (b) after removal of resin-infiltrated specimens.

exceptions all plantations were damaged with few stands over 12 metre high remaining standing. Of the 44,000 ha of forest (all species) in Canterbury at that time 11000 ha (25%) was wind thrown. Wilson pointed out that radiata pine was the major species affected, both because it was the predominant species for timber production and generally the tallest species.

The stand studied here was 25 years old when felled in 1993, i.e. it was established in 1968. According to the Canterbury Site Index Equations (Lawrence, 1988), at the time of the 1975 wind blow the trees would have a top height of 8 metre. This compares with an estimated height of the internodal top log of ca. 12 metres.

The 12 trees had average breast height diameter (dbh) of 39 cm which compares with a mean dbh of 32 cm for the 48 trees sampled indicating that they were the taller trees which would have been more susceptible to wind damage. The tops of the trees at that early age would have received the full force of the gale, strong enough perhaps to damage the young wood with resin being deposited as a result.

8.2.2.4 Comparison of positions relative to the pith (butt, middle and top logs) and growth ring numbers from the pith (internodal top logs)

The objective of identifying and cutting clearwood specimens on the basis of growth rings within a stem from the 48 short internodal top logs was directly to compare the physical and mechanical properties, determined from these specimens with those determined from specimens sawn on the basis of positions relative to the pith.

The ratios of the mean modulus of elasticity, bending strength and density values for the four growth ring numbers from the pith (Table 8.14) to those for the respective values for the four relative positions to the pith (Table 8.7) are summarised in Table 8.14. The values for positions 1 to 4 are average values for top, middle and butt logs.

Table 8.14 **Summary of the ratio of the mean MOE, MOR and density values for the four growth ring numbers to the respective values of MOE, MOR and density for the four relative positions to the pith.**

Ring number/ Position relative to the pith	Ratio (%)		
	MOE	MOR	Density
GR1 : Pos1	80.3	84.0	91.6
GR5 : Pos2	87.2	86.0	93.1
GR10 : Pos3	89.5	83.8	93.3
GN15 : Pos4	98.0	87.6	90.4

GR = growth ring; Pos = positions relative to the pith.

Table 8.14 shows that the mean values for the modulus of elasticity, bending strength and density, sorted on the basis of growth ring numbers from the pith (from internodal top logs) are lower than the respective mean values sorted on the basis of positions relative to the pith. The four positions relative to the pith contained wood from a range of growth rings at each level. However, such differences, especially for growth rings 5 to 15 and positions 2 to 4 were not expected.

The slightly lower ratio when comparing growth ring 1 and position 1 is probably due to the fact that with the internodal top log the specimens at growth ring 1 is much closer to the pith than occurs (on average) when sampling from a board from position 1 (compare the values in Tables 8.10 and 8.13). The relative values in Table 8.14 are not particularly significant as the location of these rings will be affected by growth rates so that ring 5 may occur in position 1 in a slow growth tree or in position 2 in a fast growth tree. The use of "relative positions" in Experiment 1 is more suited to sawmilling studies.

8.3 THE STATISTICAL RELATIONSHIPS BETWEEN RANKING PROPERTIES

Before the analysis of the between-tree variations it is appropriate to carry out a linear regression on the relationships between ranking properties: between stiffness and bending strength, stiffness and compression strength, between bending strength and compressive strength, and between density and stiffness, and density and bending strength.

The results of the linear regression analysis between the four variables: modulus of elasticity (MOE), bending strength (MOR), compressive (parallel to the grain) strength and density are summarised in Table 8.15. The relationships between stiffness and bending strength, stiffness and compressive strength, and stiffness and density; between compressive strength and bending strength, and between density and bending strength and density compression strength are plotted in Figures 8.5 - 8.7.

Table 8.15 **A summary of the linear regression analysis values between modulus of elasticity(MOE), bending strength (MOR), maximum crushing strength (MCS) and density.**

Independent	Dependent	N	Constant	X-Coefficient	R^2	S.E
MOE	Density	1830	426.00	5.65	0.07	38.03
	MOR	1830	30.58	4.56	0.51	8.53
	MCS	414	13.66	2.36	0.66	3.49
Density	MOR	1830	-6.38	0.16	0.26	10.25
	MCS	414	-0.81	0.07	0.29	5.06
MOR	MCS	414	2.69	0.43	0.66	3.51

S.E = A measure of the accuracy obtained when using a linear regression equation as a means of estimating the value of the dependent variable from the independent variable.

Figures 8.5a and 8.5b show that there is a significant relationship between the modulus of elasticity and bending strength and modulus of elasticity and compression strength. It can be seen from (Figures 8.5a and b) that 51% (R^2 = 0.51) of the variation in bending strength and 66% (R^2 = 0.66) of the variation in compression strength could be explained by the variations in the modulus of elasticity.

The relationship between compression parallel to the grain strength and bending strength (Figure 8.6) is also strong as 66% (R^2 = 0.66) of the variation in bending strength of clearwood could be explained by the variation in compression strength.

Regression between density and other properties (Figures 8.5c, 8.7a and 8.7b) are poor. Such poor relationships between density and stiffness, even between density and strength mean that the effects of ranking (or selection) according to density will have no significant effect on stiffness, and will only have a modest effect on strength.

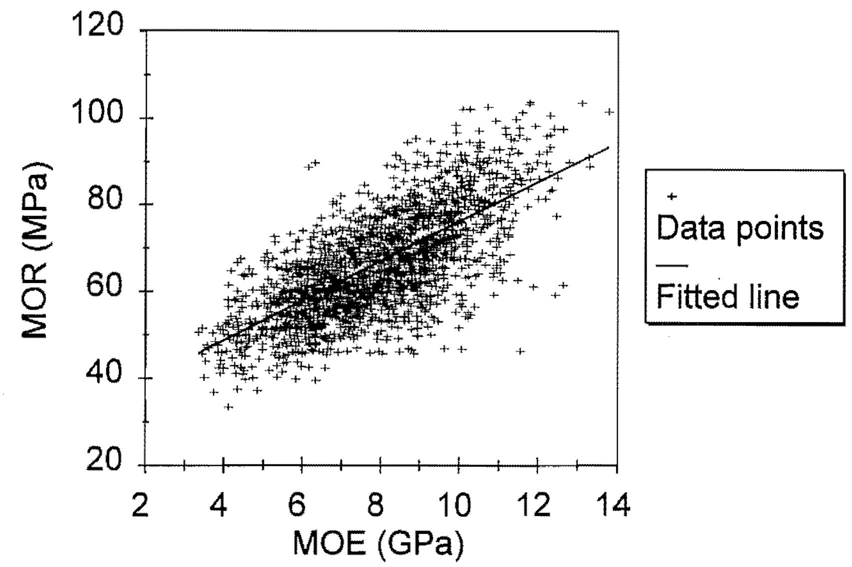


Figure 8.5a Modulus of elasticity vs bending strength.

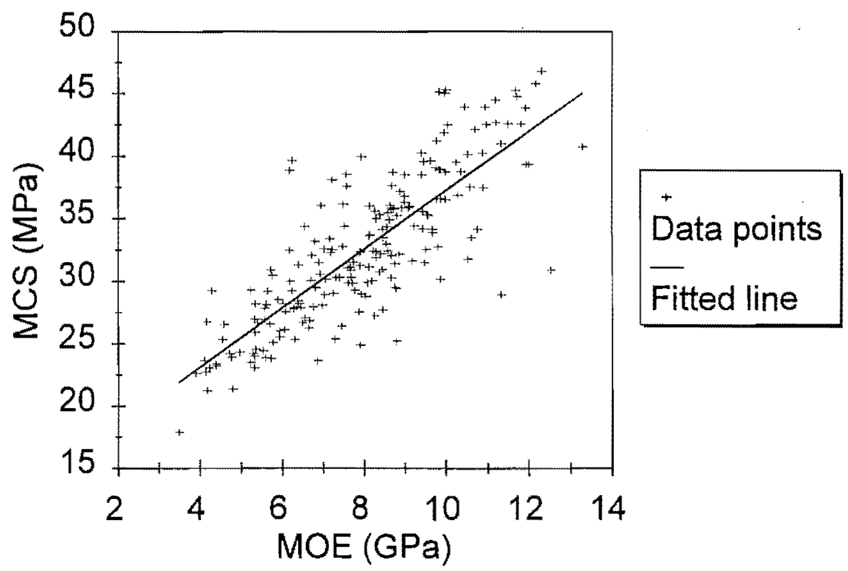


Figure 8.5b Modulus of elasticity vs compression strength.

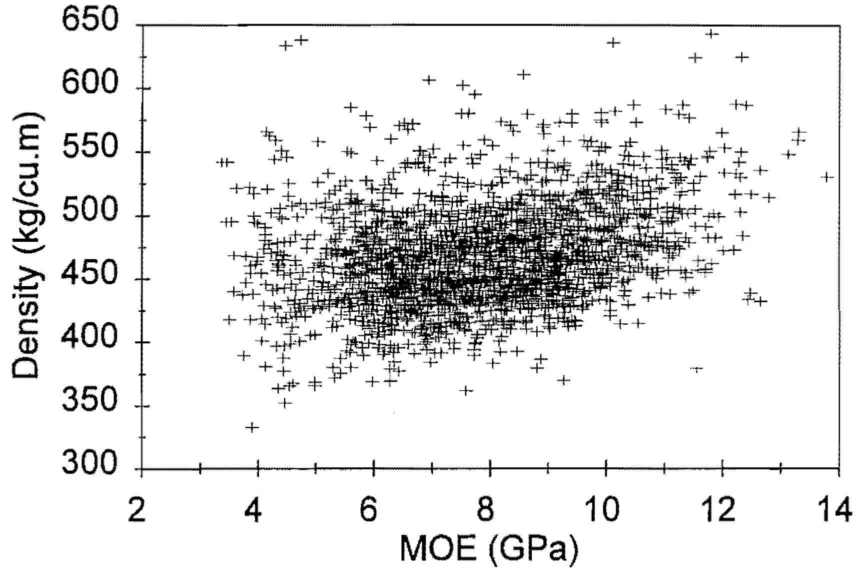


Figure 8.5c. Modulus of elasticity versus density.

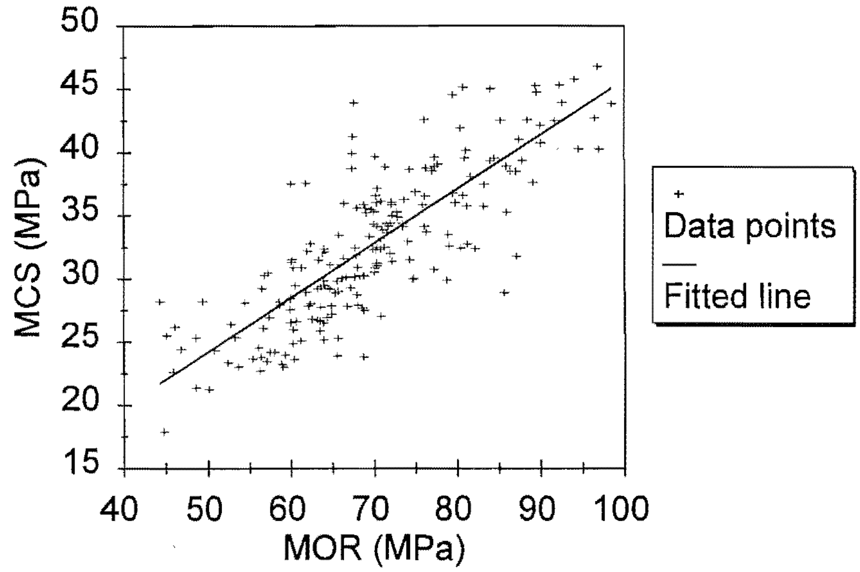


Figure 8.6 Bending strength vs compression strength.

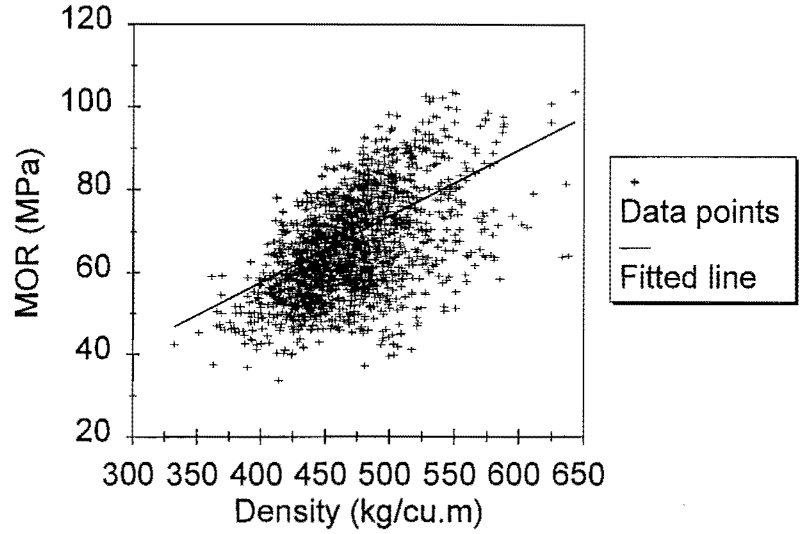


Figure 8.7a Density versus bending strength.

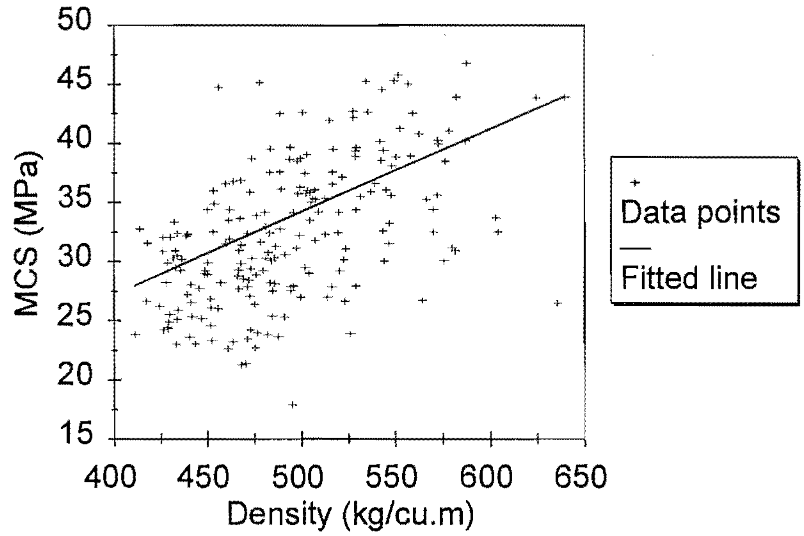


Figure 8.7b Density versus compression strength.

8.4 BETWEEN-TREE VARIATIONS

8.4.1 Procedure of ranking

The procedure of ranking clearwood according to stiffness, bending strength and density is similar to that for graded timber which is described earlier in Chapter 4. The trees were ranked to find those with five best and five worst clearwood properties. The exercise was carried out 3 times - once each for stiffness, bending strength, density.

Ranking of trees according to stiffness reveals that two of the five low stiffness trees also displayed low bending strength (trees #2 and #9), whereas four of the five high stiffness trees also displayed high bending strength (trees #3, #24, #41 and #47). Ranking of trees according to density showed that of the five low density trees none displayed low stiffness, while two displayed low bending strength (trees #12 and #45). Of the five high density trees, two of these displayed high stiffness (#3 and #24) while three displayed high bending strength (trees #3, #24 and #28). A summary of the five low and five high value tree in stiffness, bending strength and density is presented in Table 8.16

Table 8.16 **Summary of trees selected according to stiffness, tensile strength and density of clearwood.**

Property	Group (five trees in each group)	
	Low value trees	High value trees
Stiffness	#2, #9, #14, #16, #5	#3, #11, #24, #41, #47
Strength	#2, #9, #12, #45, #46	#3, #28, #24, #41, #47
Density	#32, #30, #12, #45, #13	#3, #28, #24, #37, #5

= identification numbers (1 - 48) given to the 48 trees.

8.4.2 Ranking of trees according to stiffness

a. Modulus of elasticity and bending strength

The mean values of modulus of elasticity, bending strength and density for the five low stiffness, thirty eight medium stiffness and five high stiffness trees, and the difference (%) between each group in moving from the low to the high value trees are presented in Table 8.17

Table 8.17 **Mean modulus of elasticity and bending strength for the three groups of trees ranked according to stiffness, and the difference (%) between each group: data from all log types.**

Group	# of trees	N	MOE (GPa)	Change (%)	MOR (MPa)	Change (%)	Density (kg/m^3)	Change (%)
Low	5	186	6.4 (0.8)	-	61.5 (4.6)	-	477 (23.1)	-
Medium	38	1714	7.9 (0.5)	+23.0	65.7 (3.1)	+6.8	464 (17.3)	-2.7
High	5	250	9.2 (0.2)	+16.0	75.2 (4.1)	+14.5	503 (23.1)	+8.4

Values in parentheses are standard deviation; N = number of samples.

b. **Compression parallel to the grain strength**

As discussed earlier (Chapter 3) clearwood compression specimens were selected from the boards which represented the five least stiff and five stiffest trees as determined from the tensile tests in Experiment I (graded boards). Therefore, the five low stiffness and five high stiffness trees identified in this analysis (from clearwood tests) do not necessarily coincide with those shown in Table 8.17 above. The reason why the low stiffness and high stiffness trees differed in the two Experiments will be discussed later in Chapter 9.

A summary of the mean values of compression strength for the five low and five high stiffness trees ranked according to stiffness and the difference (%) between the two extreme groups is presented in Table 8.18.

Table 8.18 **Mean compression strength (MCS) for the three groups of trees ranked according to stiffness: data from all log types.**

Group	# of trees	N	MCS (MPa)	Change (%)
Low	5	220	30.4 (5.4)	-
High	5	194	34.8 (5.8)	+14.5
Total	10	414	32.0 (7.1)	

Figures in parenthesis are standard deviation.

8.4.3 **Ranking of trees according to bending strength**

The mean values of bending strength, modulus of elasticity and density for the five weakest, thirty eight medium strength and five strongest trees ranked according to strength, and the difference (%) between each group in moving from the weakest to the strongest groups are shown in Table 8.19.

Table 8.19 **Mean modulus of elasticity and bending strength for the three groups of trees ranked according to bending strength, and the difference (%) between each group: data from all log types.**

Group	# of tree	N	MOE (GPa)	Change (%)	MOR (MPa)	Change (%)	Density (kg/m^3)	Change (%)
Weak	5	179	6.9 (1.0)	-	59.0 (3.0)	-	447 (15.0)	-
Medium	38	1723	7.8 (0.6)	+13.0	66.0 (2.6)	+11.9	467 (16.1)	+4.5
Strong	5	248	9.2 (0.3)	+17.9	75.4 (3.8)	+14.2	510 (15.0)	+9.2

Values in parentheses are standard deviation; N = number of samples.

8.4.4 **Ranking of trees according to density**

The mean values of density, bending strength and modulus of elasticity for the five low density, thirty eight medium density and five high density trees, ranked according to density, and the difference (%) between each group in moving from the low density to the high density groups are summarised in Table 8.20.

Table 8.20 **Mean modulus of elasticity and bending strength for the three groups of trees ranked according to density, and the difference (%) between each group: data from all log types.**

Group	# of tree	N	MOE (GPa)	Change (%)	MOR (MPa)	Change (%)	Density (kg/m^3)	Change (%)
Low	5	224	7.7 (0.4)	-	62.2 (3.3)	-	437 (8.50)	-
Medium	38	1671	7.8 (0.8)	+1.3	66.0 (4.2)	+6.1	467 (13.1)	+6.9
High	5	255	8.4 (1.0)	+7.7	71.7 (4.7)	+7.6	514 (11.3)	+10.1

Values in parentheses are standard deviation; N = number of samples.

8.4.5 **Discussion**

The results of ranking according to stiffness (Table 8.17) show that the stiffest trees are 44% stiffer and 22% stronger in bending than the least stiff trees. Concerning density, the stiffest trees are 8% denser than the medium stiffness trees, but only 5% denser than the least stiff trees. Thus it is surprising that the least stiff trees are denser (by 3%) than the medium stiffness trees. This result clearly demonstrates that stiffness is not a good indicator of density (Table 9.17); or more significantly, density is a poor indicator of stiffness. This is also reflected in scatter graph (Figure 8.5c).

Table 8.18 shows that the least stiff trees are about 15% stronger in compression parallel to the grain than the high stiffness trees. A direct comparison between compression strength and bending strength may not be strictly appropriate, because of between-tree differences in the ranking of trees according to stiffness in the two experiments. However, the 15% difference in compression strength between the low and high stiffness trees (Table 8.18) is less than the 22% difference in bending strength (Table 8.17) between the same group of trees ranked according to stiffness.

Ranking according to bending strength (Table 8.19) shows that the strongest trees are 28% stronger, 33% stiffer and 14% denser than the weakest trees. The 14% density difference between the strongest and weakest trees ranked according to bending strength is almost three times as much as the 5% difference between the stiffest trees and least stiff trees ranked according to stiffness (Table 8.17).

Table 8.20 shows the potential improvement in density, bending strength and stiffness by ranking trees according to density. It can be seen from Table 8.20 that the high density trees are 18% denser than the low density trees. In the case of strength and stiffness, however, only a modest increase (15% and 9% respectively) between the low density and high density trees is achieved, with no significant difference between the medium and low density trees, and the medium and high density trees.

8.5 MAIN EFFECT ANALYSIS

The importance of a two-way analysis of variance test to compare the effects of the within-tree (i.e. positions relative to the pith and log types) and between-tree variations has been discussed and demonstrated earlier in Chapter 5, for the properties of the graded boards. In this section a similar comparison is made on the effect of positions relative to the pith, log types and trees on modulus of elasticity, bending strength and density of clearwood. The results of the two-way analysis of variance test for modulus of elasticity, bending strength and density are summarised in Tables 8.21 - 8.23.

Table 8.21 **A summary of the results of the analysis of variance test for the modulus of elasticity (MOE).**

Source of variation	DF	Sum of Squares (SS)	Variance Component (%)	Mean Square (MS)	F-Value	Pr > F
Trees	47	1112.8	18.2	23.7	23.7	**
Log type	2	134.4	2.2	67.2	67.2	**
Pos.	3	2810.3	45.9	936.8	936.8	**
Trees x Logs	92	388.8	6.3	4.2	4.2	*
Trees x Pos.	103	49.2	0.8	0.5	0.5	ns
Logs x Pos.	5	96.1	1.6	19.2	19.2	**
Trees x Logs x Pos.	153	148.3	2.4	1.0	1.0	ns
Model Total	405	4739.9	77.4	11.7	11.7	**
Error	1424	1382.8	22.6	1.0		
Total	1829	6122.8	100.0			

Table 8.22 **A summary of the results of the analysis of variance test for the modulus of rupture (MOR).**

Source of variation	DF	Sum of Squares (SS)	Variance Compt. (%)	Mean Square (MS)	F-Value	Pr>F
Trees	47	35682.5	13.7	759.2	17.7	**
Log type	2	3887.1	1.5	1943.5	45.3	**
Pos.	3	119913.1	46.0	39971.0	931.7	**
Trees x Logs	92	23108.9	8.9	251.2	5.8	*
Trees x Pos.	103	7510.3	2.9	72.9	1.7	ns
Logs x Pos.	5	0.0	0.0	0.0	0.0	ns
Trees x Logs x Pos.	153	9523.0	3.5	62.2	1.4	**
Model Total	405	199624.9	76.5	492.0	11.5	
Error	1424	61161.0	23.5	42.9		
Total	1829	260785.9	100.0			

Table 8.23 **A summary of the results of the analysis of variance test for density.**

Source of variation	DF	Sum of Squares (SS)	Variance Compt. (%)	Mean Square (MS)	F-Value	Pr>F
Trees	47	899922.2	31.2	19147.3	39.3	**
Log type	2	321681.6	11.1	160840.8	330.5	**
Pos.	3	402112.2	13.9	134037.4	275.4	**
Trees x Logs	92	305855.3	10.6	3324.5	6.8	**
Trees x Pos.	103	164269.0	5.7	1594.8	3.3	*
Trees x Logs x Pos.	153	99915.5	3.5	653.0	1.3	ns
Model Total	405	2193755.8	76.0	5416.7	11.1	**
Error	1424	692940.0	24.0	486.6		
Total	1829	2886695.8	100			

Pos. = positions relative to the pith; x = interaction; ** = p< 0.01; * = p< 0.05; ns = not statistically significant.

Tables 8.21 - 8.23 show that the two-way analysis of variance test model used to determine the variability of modulus of elasticity, bending strength and density due to the effect of trees, positions relative to the pith and log types was statistically acceptable. This can be seen from the high percentage values of the variance component for all properties: compared to the error effect the model contributes 77% for the modulus of elasticity and bending strength (Tables 8.21 and 8.22), and 76% for density.

The effects (i.e. the percentages of the variance component) of trees, log types and positions relative to the pith on the modulus of elasticity, bending strength or density are also examined. For modulus of elasticity (Table 8.21) and bending strength (Table 8.22), positions relative to the pith (radial distance across the diameter) contributes the highest (46%) variation in both properties followed by between-tree variation (18% for modulus of elasticity and 14% for bending strength). Log types (vertical distance up the height of the tree) contributes the least effect (2%) in both modulus of elasticity and bending strength. For density (Table 8.23), however, the effect of trees is the highest (31%) followed by positions relative to the pith (14%) and log types (11%).

The within-tree variations observed here for modulus of elasticity, bending strength and density are very similar with those reported by Smith *et al.* (1991) for red pine (P.resinosa). They measured modulus of elasticity (from dynamic bending), static bending strength and other mechanical properties (shear moduli and viscous damping ratios, all from dynamic tests) and density in clearwood (25x25x350 mm) specimens cut from 54-year-old red pine from New Brunswick, Canada. They examined all properties as a function of radial and vertical positions in the stem. The radial positions were divided according to distance (mm) from pith and the vertical positions according to 4 vertical distances (m) up the height of the tree. Their results showed that the primary influences on wood quality were radial positions from the pith.

CHAPTER 9: **COMPARISONS BETWEEN THE PROPERTIES OF TIMBER (EXPERIMENT I) AND CLEARWOOD (EXPERIMENT II)**

9.1 **INTRODUCTION**

Madsen (1984) has emphasised that "timber" and "clearwood" should be treated as two different materials since their failure modes and resulting strengths are totally different: clearwood fails in tension parallel to the grain as a consequence of shear failure in the middle lamella between tracheids. Timber fails in tension perpendicular to the grain (splitting) at defects. In compression clearwood fails by the buckling of individual cells over the cross section while timber involves crushing of wood cells perpendicular to the grain. In bending clearwood is stronger in tension than it is in compression. Therefore, when clearwood is subjected to bending the failure in the tension zone is preceded by the formation of wrinkles in the compression zone. This results in a somewhat ductile behaviour just before failure. Timber on the other hand contains growth characteristics such as knots. Such localised grain disturbances result in tensile stresses perpendicular to the grain, leading to a brittle fracture failure mode at tensile stress levels which are lower than the compressive strength.

Apart from their failure modes there is the size effect (Madsen and Buchanan, 1986) which also results in higher failure stresses for clearwood compared with timber, because clearwood specimens are smaller in size.

From the above description of the two materials (timber and clearwood) Madsen concluded that we cannot obtain strength values from clearwood specimens and use them as a base for timber design because the failure modes governing the behaviour of the two are different.

As a consequence of this re-thinking there has been an international move to desire design stresses from in-grade testing rather than the traditional reliance on small clearwood specimens. This has been assisted by the move from the basic working stress (WSD) to limits states design (LSD) codes.

As stated in Chapter 1 one of the main objectives of this thesis is to examine the relationship between the stiffness of clearwood and timber: to see whether there is a significant correlation between the two which would enable the stiffness of timber to be predicted from that of clearwood. In addition, the thesis examines within-tree changes in properties as a function of radial distance from the pith and vertical distance up the height of the tree. This chapter examines these changes in the stiffness, strength and density in both materials (timber and clearwood) and computes the ratio for each property in timber to that in clearwood.

First, a comparison will be made of the trends in modulus of elasticity, strength properties and density between the graded timber (Experiment I) and clearwood (Experiment II) with changes in vertical and radial positions within a tree;

Secondly, a brief review of the results arising from ranking of trees according to stiffness, strength and density will be made;

Finally, a linear regression analysis will be made between the properties of the graded timber and clearwood.

9.2 A COMPARISON OF WITHIN-TREE VARIATIONS OF MECHANICAL AND PHYSICAL PROPERTIES OF TIMBER AND CLEARWOOD

This section compares the within-tree variations in mean modulus of elasticity, compression parallel to the grain strength, bending strength and density in both timber and clearwood. The ratio of timber property to that for clearwood; for the whole tree, four positions relative to the pith and three log types will also be calculated separately.

9.2.1 Modulus of elasticity

The mean modulus of elasticity values for graded timber and for clearwood cut from these boards, segregated on the basis of the four positions relative to the pith and the three log types are summarised in Tables 9.1 and 9.2.

Table 9.1 **The mean modulus of elasticity of the graded timber and of clearwood, on the basis of the four positions relative to the pith.**

Experiment	MOE (GPa) by position relative to the pith				All
	1	2	3	4	
I (Timber)	4.9 (206)	6.7 (440)	8.5 (250)	9.3 (19)	6.8 (915)
II (Clearwood)	6.1 (412)	7.8 (880)	9.5 (500)	10.2 (38)	7.9 (1830)
Ratio	0.80	0.86	0.89	0.91	0.86

Values in parenthesis are number of samples.

Table 9.2 **The mean modulus of elasticity of the graded timber and of clearwood, on the basis of the three log types.**

Experiment	MOE (GPa) by Log type			All
	Top log	Middle log	Butt log	
I (Timber)	6.7 (221)	7.0 (295)	6.8 (399)	6.8 (915)
II (Clearwood)	7.7 (442)	8.3 (590)	7.7 (798)	7.9 (1830)
Ratio	0.87	0.84	0.88	0.86

Values in parenthesis are number of samples.

Tables 9.1 and 9.2 show that, irrespective of the radial position across the diameter or the vertical position up the height of the tree, the ratio of the modulus of elasticity of the graded timber to that of clearwood ranges from 0.80 to 0.90 with average ratio of 0.86. The ratio reflects the effect of defects on the stiffness of in-grade timber.

Table 9.1 shows that the ratio of the mean modulus of elasticity values of the graded timber to those of clearwood increases from the pith to the cambium. One reason for the low ratio in position 1 could be that the timber in position 1 contains pith, whereas clearwood is pith-free.

Table 9.2 shows that for both materials (graded timber and clearwood) the mean modulus of elasticity is the highest at the middle log, and the reason for such a high value is unknown.

9.2.2 **Compression strength parallel to the grain**

A total of four hundred and fourteen 60 mm long, 20x20 mm samples were used for the small clear compression test. They consisted of two discrete populations. Specimens for compression testing came from boards belonging to the five highest and five lowest stiffness trees as determined in Experiment I.

The mean compressive strength values of the graded timber and clearwood samples, determined for the five highest and five lowest stiffness trees are presented in Tables 9.3 and 9.4, segregated according to the four positions relative to the pith and the three log types respectively. Data are derived by merging the high and low stiffness populations. A comparison between the two discrete populations is also shown in Appendix 5.

Table 9.3 **The mean compression strength (MCS) of graded timber and clearwood, on the basis of the four positions relative to the pith: data from the five highest and five lowest stiffness trees.**

Experiment	MCS (MPa) by position relative to the pith				All
	1	2	3	4	
I (Timber)	23.6 (41)	25.6 (97)	28.2 (62)	30.7 (7)	26.2 (207)
II (Clearwood)	26.6 (82)	31.2 (194)	37.5 (124)	40.2 (14)	32.5 (414)
Ratio	0.89	0.82	0.75	0.76	0.81

Values in parenthesis are number of samples.

Table 9.4 **The mean compression strength (MCS) of graded timber and clearwood, on the basis of the three log types: data from the five highest and five lowest stiffness trees.**

Experiment	MCS (MPa) by Log type			All
	Top log	Middle log	Butt log	
I (Timber)	25.0 (51)	26.6 (65)	27.1 (91)	26.2 (207)
II (Clearwood)	31.1 (102)	32.7 (130)	33.1 (182)	32.5 (414)
Ratio	0.80	0.80	0.82	0.81

Values in parenthesis are number of samples.

Tables 9.3 and 9.4 show an overall ratio of 0.81 which indicates the effects of specimen size (280 x 90 x 35 mm for timber versus 60x20x20 mm clearwood) and defects (knotty for timber versus clearwood).

Table 9.3 shows that the ratio of compression strength parallel to the grain for graded timber to that for clearwood decreases in going from the pith towards the cambium. As discussed earlier (Chapters 3 and 4) the compression samples for the graded timber (Experiment I) were cut from timber which had already been tested in tension.

The timber was cut to include the worst visible defect (knot) remaining in each board after testing in tension (Experiment I). One possible argument could be that the branch size and knot size increases in moving away from the pith. Therefore, the cross-sectional area ratio of each knot (KAR) increases in going away from the pith to the cambium, and consequently the ratio of the compressive strength for timber to that for clearwood would decrease.

The ratios (i.e. 0.75 - 0.89) in Tables 9.3 and 9.4 for the compressive strength should be taken cautiously for two reasons:

First, as explained earlier (Chapter 3), the compression samples for the graded timber (Experiment I) were cut from timber already tested in tension, on the basis of the worst remaining visible defect (knot) on the each board. From this point of view the compression strength value for the worst visible defect in the original graded boards could have been lower than that measured in this experiment.

Secondly, the two extreme sub-populations may not be a true representative of the population as a whole.

9.2.3 **Tensile strength (timber) and bending strength (clearwood)**

The bending strength was measured for only the clearwood samples (Experiment II), while the tensile strength was measured for only the graded timber (Experiment I). Therefore, in this section, the mean tensile strength values for the graded timber will be compared with the mean bending strength values for the clearwood specimens.

Tables 9.5 and 9.6 present the mean tensile strength values for the in-grade samples and the mean bending strength values for the clearwood specimens, sorted according to positions relative to the pith and log types.

Table 9.5 **The mean tensile strength (UTS) of the graded timber and the mean bending strength (MOR) of clearwood specimens, on the basis of the four positions relative to the pith.**

Experiment	UTS/MOR (MPa) by position relative to the pith				All
	1	2	3	4	
I (Timber) UTS values	13.5 (206)	17.8 (440)	23.2 (250)	29.1 (19)	18.6 (915)
II (Clearwood) MOR values	56.3 (412)	64.5 (880)	77.3 (500)	86.3 (38)	66.6 (1830)
UTS/MOR ratio	0.24	0.28	0.30	0.34	0.28

Values in parenthesis are number of samples.

Table 9.6 **The mean tensile strength (UTS) of the graded timber and the mean bending strength (MOR) of clearwood specimens, on the basis of the three log types.**

Experiment	UTS/MOR (MPa) by Log type			All
	Top log	Middle log	Butt log	
I (Timber) UTS values	15.2 (221)	17.9 (295)	20.9 (399)	18.6 (915)
II (Clearwood) MOR values	64.4 (442)	66.4 (590)	68.1 (798)	66.6 (1830)
UTS/MOR ratio	0.24	0.27	0.31	0.28

Values in parenthesis are number of samples.

Tables 9.5 and 9.6 show that the biggest changes are occurring in the tensile strength of timber not in the bending strength of clearwood.

9.2.4 **Density**

There is no noticeable difference in density between the 90x35 mm clearwood samples (Experiment I) and 20x20 mm clearwood samples (Experiment II). A summary of the density of timber and clearwood, sorted according to the four positions relative to the pith and three log types is presented in Tables 9.7 and 9.8.

Table 9.7 **Mean density of the graded timber and clearwood samples, on the basis of the four positions relative to the pith.**

Experiment	Density (kg/cu.m) by position relative to the pith				All
	1	2	3	4	
I (Timber)	464 (206)	470 (440)	489 (250)	514 (19)	475 (915)
II (Clearwood)	455 (412)	465 (880)	490 (500)	521 (38)	471 (1830)
Ratio	1.02	1.01	1.00	0.99	1.01

Values in parenthesis are number of samples.

Table 9.8 **Mean density of the graded timber and clearwood samples, on the basis of the three log types.**

Experiment	Density (kg/cu.m) by Log type			All
	Top log	Middle log	Butt log	
I (Timber)	462 (221)	462 (295)	492 (399)	475 (915)
II (Clearwood)	457 (442)	461 (590)	486 (798)	471 (1830)
Ratio	1.01	1.00	1.01	1.01

Values in parenthesis are number of samples.

9.3 COMPARISONS OF BETWEEN-TREE VARIATIONS FOR TIMBER AND CLEARWOOD PROPERTIES

9.3.1 Ranking of trees according to stiffness, strength and density

In earlier discussion (Chapters 4 and 7) the between-tree differences in the mean modulus of elasticity, tensile strength, compressive strength, bending strength and density were examined by ranking the 48 trees according to mean stiffness, strength and density. Trees were placed in the low, medium or high value groups for a particular property (stiffness/strength/density), both when tested in tension as sawn timber and in bending as clearwood. Those trees that were classified as either low or high categories both in sawn timber and in clearwood are listed in Table 9.9.

Table 9.9 **Trees selected according to extremes in stiffness, strength and density in both Experiments I and II.**

Property	Group			
	Low value trees		High value trees	
	Trees	Total	Trees	Total
Stiffness	#2, #16, #5	3	#3, #11, #24, #41	4
Strength	#46	1	#3, #24	2
Density	#12, #32, #45	3	#5, #24, #28, #37	4

= identification numbers (1 - 48) given to the 48 trees.

The individual tree numbers in Table 9.9 are those trees which were assigned to the high or low value groups for both the timber tests (Experiment I) and the clearwood tests (Experiment II).

When selecting for density or stiffness seven outlying trees (either high or low categories) retain their grouping whether ranked as sawn timber or clearwood. As density was determined from defect free specimens in both experiments the outturn of high number of trees in ranking according to density is not surprising. It is interesting to note that in both experiments one high density tree (#5) displayed low stiffness.

Concerning strength, the lower number of trees ranked according to strength in both timber and clearwood specimens is expected, because different modes of testing and failure apply in the two experiments.

9.3.2 **Timber and clearwood properties**

The mean modulus of elasticity, compression strength and density for the graded timber (Experiment I) and those for clearwood specimens (Experiment II), for the three groups of trees ranked according to stiffness, strength and density are presented in Tables 9.10 - 9.13. The five lowest and five highest value trees in stiffness, strength and density are from each experiment, i.e. they are not the same trees.

Table 9.10 **Mean modulus of elasticity (MOE) of timber and clearwood for the three groups of trees, ranked according to stiffness.**

Experiment	MOE (GPa) for the three groups of trees		
	Low stiffness	Medium stiffness	High stiffness
I (Timber)	4.7	6.5	8.4
II (Clearwood)	6.4	7.9	9.2
Ratio	0.73	0.82	0.91

Table 9.11 **Mean compression strength (MCS) of timber and clearwood for the three groups of trees, ranked according to stiffness.**

Experiment	MCS (MPa) for the two groups of trees*	
	Low stiffness	High stiffness
I (Timber)	24.8	27.8
II (Clearwood)	30.4	34.8
Ratio	0.82	0.80

*Compression strength was not measured for the medium stiffness trees in clearwood specimens.

Table 9.12 **Mean tensile strength (UTS) of timber and bending strength (MOR) of clearwood for the three groups of trees, ranked according to strength.**

Experiment	UTS/MOR (MPa) for the three groups of trees		
	Low strength	Medium strength	High strength
I (Timber) UTS values	11.3	20.3	27.2
II (Clearwood) MOR values	59.0	66.0	75.4
UTS/MOR ratio	0.19	0.31	0.36

Table 9.13 **Mean density of timber and clearwood for the three groups of trees, ranked according to density.**

Experiment	Density (kg/cu.m) for the three groups of trees		
	Low density	Medium density	High density
I (Timber)	450	489	542
II (Clearwood)	437	467	514
Ratio	1.03	1.05	1.05

Table 9. 10 shows that the ratios of timber stiffness to clearwoodstiffness increases

from 0.73 for the low stiffness trees to 0.91 for the high stiffness trees. This suggests that the effect of defects such as knots on stiffness decreases in the high quality material.

Table 9.11 shows that the ratio of compressive strength for the in-grade and small clear specimens is almost the same for the low stiffness and high stiffness trees. The similarity in the ratio is expected as defects have little effect on compressive strength compared to tensile strength or modulus of elasticity.

Ratio of tensile strength to bending strength (Table 9.12) increases from 0.19 for the weakest to 0.36 for the strongest trees. This suggests (similar to the case for MOE, Table 9.10) that the effect of defects on tensile strength decreases in the high quality material.

9.4 LINEAR REGRESSION ANALYSIS BETWEEN THE PROPERTIES OF TIMBER AND CLEARWOOD

It was clearly shown above (Sections 9.2 and 9.3) that there is a steady trend of within- and between-tree variation in all properties regardless of the nature of the material (i.e. timber or wood) in which the property is measured. However, these trends do not indicate whether it would be possible to predict the property of an individual piece of timber from that of clearwood, both taken from the same material. Therefore, linear regression analysis was performed to examine this one-to-one relationship between pairs of data points obtained from the two materials.

In matching each of the 915 data points for the modulus of elasticity, tensile strength and density of the graded timber (Experiment I) with those for clearwood (Experiment II), the respective averaged values (from a pair of matching 20x20 mm clearwood samples cut from a single board) of the modulus of elasticity, bending strength and density were used. For compressive strength, only 207 data points for the graded timber were available to match with those of the 207 pairs of data points for the clearwood compression samples.

9.4.1 **Modulus of elasticity**

The relationship between the modulus of elasticity of clearwood (in the x-axis) and the modulus of elasticity values of the graded timber(in the y-axis) for the 915 data points is shown in Figure 9.1. The linear regression shows that there is a strong relationship (R^2 = 0.76) between the modulus of elasticity of clearwood and the in-grade timber. Thus about 76% of the variation in the modulus of elasticity of timber could be explained by the modulus of elasticity of clearwood using the regression given by Equation 9.1 as follows:

$$E_T = 0.92E_{CW} - 0.45 \qquad (9.1)$$

Where: E_T = modulus of elasticity of timber (GPa)

E_{CW} = modulus of elasticity of clearwood (GPa)

9.4.2 **Compression parallel to the grain strength**

The relationship between the compressive strength of clearwood and the compressive strength of the graded timber for the 207 data points is shown in Figure 9.2. The linear regression analysis shows that there is a very poor correlation (R^2 = 0.25) between the compression strength of clearwood and that of the in-grade timber. This means that only about 25% of the variation in the compression strength of timber could be explained by the compression strength of clearwood.

9.4.3 **Bending strength and tensile strength**

As already mentioned (Section 9.2.3) the bending strength was measured for the clearwood samples only (Experiment II), while the tensile strength was measured for the graded timber only (Experiment I).

The relationship between the bending strength of clearwood and tensile strength of the graded timber is shown in Figure 9.3. Linear regression analysis shows that there is no significant relationship (R^2 = 0.05)) between the bending strength of clearwood and the tensile strength of timber. The poor result is to be expected because the small clearwood specimens bending tests essentially measure the compression strength of clearwood whereas the in-grade tension strength measures the effects of knots and other defects in the tension zone. This only confirms the arguments of Madsen (1984) that there is no reason why these two properties should be closely related.

9.4.4 **Density**

The relationship between the density of clearwood and the density values of the graded timber for the 915 data points is shown in Figure 9.4. As expected linear regression analysis shows that there is a strong relationship (R^2 = 0.71) between the density of the clearwood samples in Experiment I and the clearwood samples in Experiment II.

9.5 **SUMMARY**

The main theme of this thesis is centred on improving radiata pine timber for structural purposes, especially its stiffness. As listed in Chapter 1 one of the main objectives of the research programme is to determine whether there is a correlation between the stiffness of timber with that of clearwood.

Regression analysis shows that there is a strong relationship (R^2 = 0.76) between the stiffness of in-grade timber and clearwood. The results in this chapter generally indicate that modulus of elasticity is one property that could be replicated regardless of the nature of material used for its determination (i.e. timber or clearwood).

The strong correlation between the stiffness of timber and clearwood observed in this study can be used for subsequent in-depth studies into the relationships between stiffness of wood and corresponding wood quality characteristics (such as density, compression wood, chemical composition, microfibril angle and cellulose quantity and quality and spiral grain), so that the fundamental parameters most influencing stiffness can be identified and considered for genetic manipulation or selecting of logs for thinning or processing options.

The strong correlation (R^2 = 0.71) between the density of clearwood cut from the in-grade timber and that of the small clearwood samples is to be expected. Whether this correlation can be usefully exploited is a matter of some controversy.

In the previous chapter (Chapters 4) we show that ranking of trees according to density does not give a good prediction of machine stress grade. This is not unexpected, in that the grading criterion is stiffness. If machine stress grade is the most important indicator of wood value (as in structural engineering), then trees should be bred for stiffness not density. This means that future studies should directly address factors which affects the stiffness of wood (Cave and Walker, 1994).

The poor regression (R^2 = 0.25) between the compression strength of the in-grade timber (Experiment I) and clearwood (Experiment II), leading to a conclusion that compression strength of clearwood cannot be used to predict that of timber.

The poor regression (R^2 = 0.05) between the tensile strength of the in-grade timber (Experiment I) and bending strength of clearwood (Experiment II) are expected, as the failure modes in the two materials are totally different.

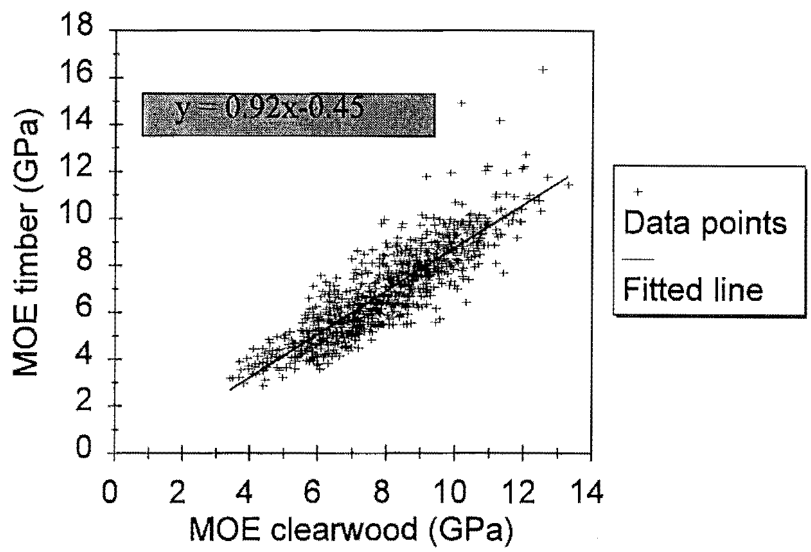


Figure 9.1 In-grade stiffness versus clearwood stiffness.

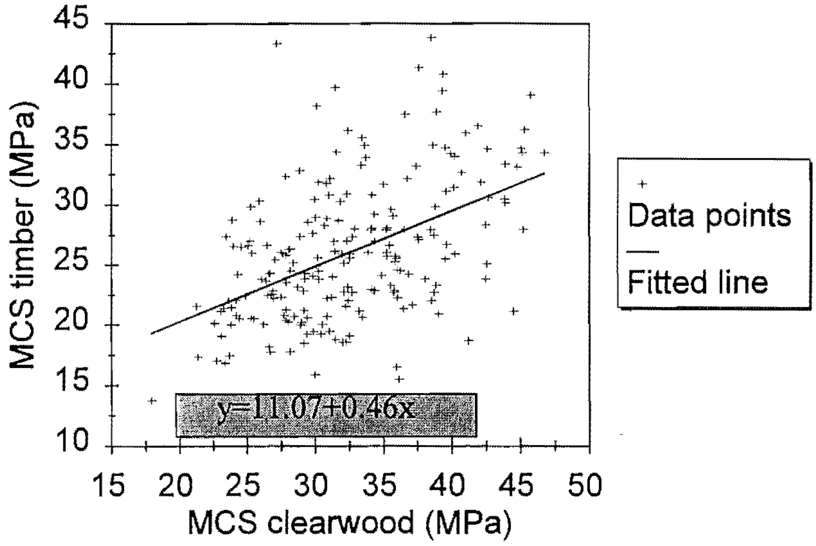


Figure 9.2 MCS timber versus MCS clearwood

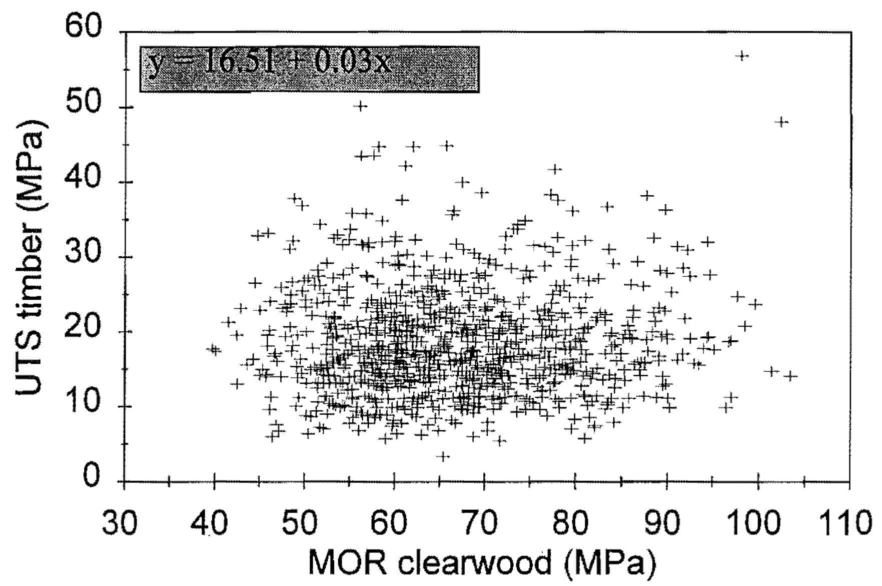


Figure 9.3 UTS timber versus MOR clearwood.

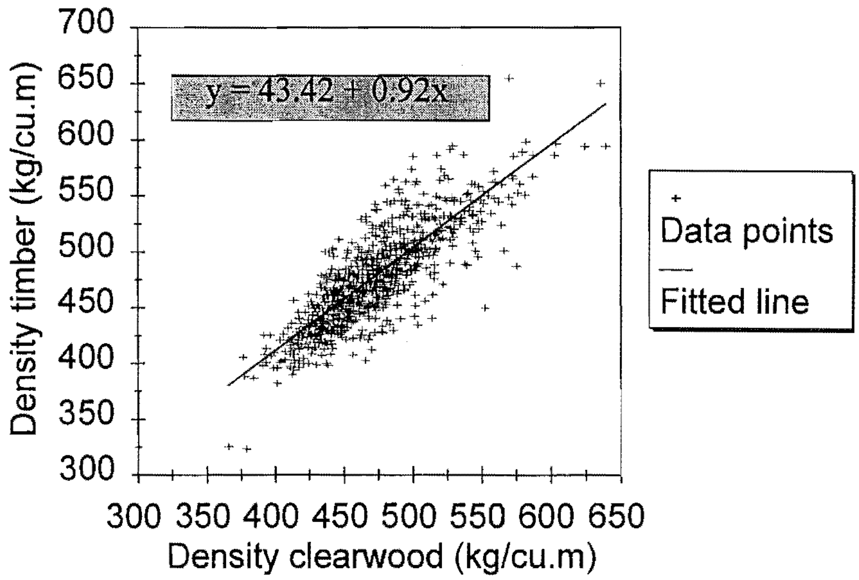


Figure 9.4 Density of timber versus density of clearwood.

CHAPTER 10: **SPIRAL GRAIN, COMPRESSION WOOD AND TREE VOLUME**

10.1 **INTRODUCTION**

In Chapters 4 and 7 variations in density, strength and stiffness due to changes in radial and vertical positions and due to changes between trees have been examined. However, this analysis was made without any consideration of any effects due to spiral grain and compression wood on the density, strength and stiffness properties of wood. In this chapter the effects of spiral grain and compression wood are examined.

A further point to consider is tree volume. The low and high quality trees were segregated by ranking trees according a particular property (stiffness, strength and density, Chapters 4 and 8). Such ranking of trees takes no account of any differences in stem volume, so an analysis of wood properties related to tree volume be carried out.

10.2 **SPIRAL GRAIN**

10.2.1 **Test specimens**

It was assumed that the within-board variations in the angle of spiral grain would be small. Hence, the angle of spiral grain was measured for only one of the two matching clearwood (20 x 20 x 300 mm) bending specimens cut from each of the nine hundred and fifteen boards tested in tension (Chapter 3).

10.2.2 **Results**

The values of the spiral grain angle for all the 915 specimens are presented in Appendix 2A. The mean angle of spiral grain on the basis of the four positions relative to the pith and three log types are summarised in Tables 10.1 and 10.2.

Table 10.1 **A summary of the mean angle of spiral grain based on positions relative to the pith.**

Position relative to the pith	N	Angle of spiral grain (^{O})	
		Mean	SD
1	206	4.2	2.4
2	440	2.8	2.5
3	250	1.9	1.9
4	19	1.8	1.6
All	915	2.9	2.5

Table 10.2 **A summary of the mean angle of spiral grain based on log types.**

Log type	N	Angle of spiral grain (^{O})	
		Mean	SD
Top	221	2.9	2.4
Middle	295	3.3	2.5
Butt	399	2.5	2.5
All	915	2.9	2.5

10.2.3 **Discussion**

Tables 10.1 and 10.2 show that the angle of spiral grain decreases significantly in moving radially from the pith to the cambium, and decrease slightly in moving vertically from the butt up the height of the tree. These results are in line with those reported by Langlands (1938) and Cown *et al.* (1991b) for radiata pine.

Langlands (1938) examined angle of spiral grain in clearwood (20x20 mm) specimens on 22-, 23-, 33- and 52-year-old plantation grown radiata pine trees in Australia. He reported that all his trees contained spiral grain near the pith, but in every case the slope of grain decreased with increasing distance from pith (in general from more than 5 degrees near the pith to less than 2 degrees near the bark), showing that this defect is much less important in the outerwood of older trees (i.e. 33 -year-old and above).

Cown *et al.* (1991b) examined spiral grain in a 25-year-old radiata pine trees from Kaingaroa Forest, New Zealand. They reported that grain angles in excess of 5 degrees are found within the first 10 growth rings from the pith, and the decline is more gradual than previously suggested (Harris, 1978), that the "zero" angle situation does not occur until about 15 rings from the pith. In contrast Harris had indicated that spiral grain peaked around ring 3 and declined thereafter whereas this new research found that the decline is much more gradual.

10.2.4 **The effects of the angle of spiral grain on wood properties**

Data on the angle of spiral grain and bending strength and angle of spiral grain and modulus of elasticity for all the 915 clearwood specimens are plotted in Figures 10.1a and b.

Regression analysis shows that 16% of the variation ($r = -0.40$) in the bending strength and 10% of the variation ($r = -0.32$) in the modulus of elasticity of clearwood specimens could be explained by the variations in the angle of spiral grain.

In order to examine the implications of the above regression analysis all the 915 data points for density, bending strength and modulus of elasticity were sorted on the basis of angle of spiral grain. It can be seen from Appendix 2A that the minimum and maximum values of the angle of spiral grain were 0 and 10.5 degrees. Once the sorting was completed, all the 915 data points were divided into 11 one-degree angle of spiral grain classes, each data point falling into one of these classes (i.e. each class representing 1 degree of spiral grain angle, except the first class with a 0 degree angle).

The objective of the above classification was to show the effect of a one-degree angle of spiral grain on bending strength, modulus of elasticity and density. A summary of mean angle of spiral grain, bending strength, modulus of elasticity and density distribution among the eleven 11 one-degree angle of spiral grain classes is presented in Table 10.3.

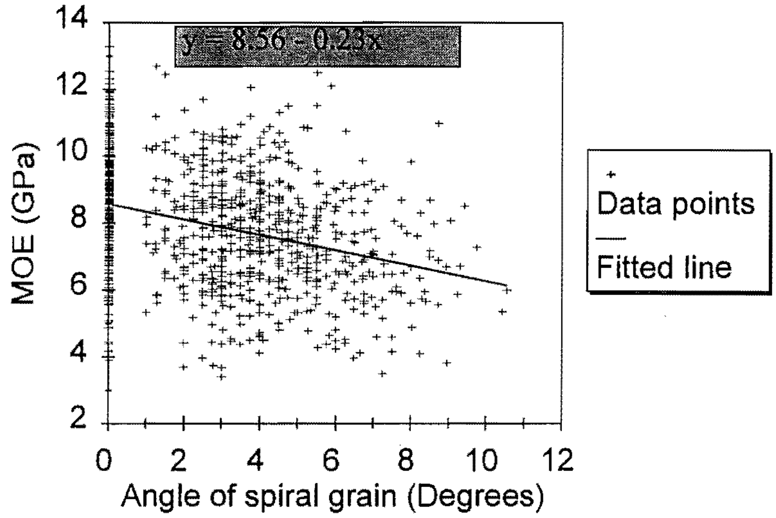


Figure 10.1a Stiffness versus angle of spiral grain.

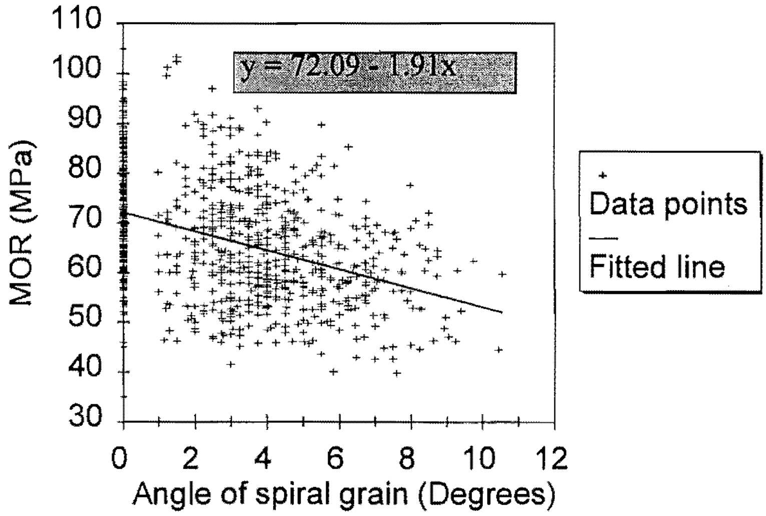


Figure 10.1b Bending strength versus spiral grain.

Table 10.3 **Distribution of man angle of spiral grain, modulus of rupture (MOR), modulus of elasticity (MOE) and density on the basis of one-degree angle of spiral grain classes.**

Class	N	Angle of spiral grain (°)	MOR (MPa)	MOE (MPa)	Density (kg/cu.m)
0	294	0.0	72.8 (11.5)	8.6 (1.7)	480 (40.3)
1	47	1.4 (0.3)	68.0 (15.1)	8.4 (1.9)	471 (46.1)
2	110	2.4 (0.3)	67.4 (12.0)	7.9 (1.7)	468 (36.3)
3	152	3.4 (0.3)	66.5 (11.6)	7.7 (1.7)	471 (36.5)
4	122	4.3 (0.3)	63.3 (9.5)	7.7 (1.6)	459 (35.5)
5	76	5.4 (0.3)	61.0 (10.4)	7.5 (1.6)	461 (41.6)
6	55	6.4 (0.3)	59.2 (7.6)	6.9 (1.5)	469 (36.3)
7	31	7.3 (0.3)	56.6 (8.1)	6.6 (1.4)	465 (43.1)
8	20	8.4 (0.3)	59.4 (9.5)	6.9 (1.7)	475 (37.1)
9	6	9.3 (0.3)	53.1 (6.8)	6.7 (1.7)	453 (27.7)
10	2	10.5	48.4	5.4	495
All	915	2.9 (2.5)	66.8 (12.2)	7.9 (1.8)	471 (39.4)

Value in parenthesis is a standard deviation.

Table 10.3 shows a decreasing trend in bending strength and stiffness with increasing spiral grain. For example, using the regression equations the bending strength and stiffness are only 66% and 63% respectively, of the value for straight grained timber for a spiral grain of 10°, and 84% and 87% respectively, of the straight grained values when the grain angle is 5°.

However, using the empirical Hankinson equation (Equation 2, Chapter 2), the value for bending strength is 59% and for modulus of elasticity 81% of the straight grained values when the grain angle is 10°.

Concerning the impact of spiral grain on the grade outturn of sawn timber, Cown *et al.* (1991b) reported that a 5-degree grain deviation is the critical point above which twist is sufficient to down grade the timber (according to the New Zealand Standard, NZS3631: 1991). Appropriate restraint during drying will mitigate its worst effects but will not wholly overcome the problem.

The effect of spiral grain angle on the grade outturn can be estimated for the current material. Spiral grain in clearwood (20 x 20 x 300 mm) specimens reflect the nature of this property in the 90 x 35 mm graded boards from which the clearwood specimens were cut. Thus, the data shown in Table 8.3 indicates that from a total of 915 graded boards 114 (12%) have angle of spiral grain > 5 degrees. This means that 12% of the sawn timber could be potentially down graded.

In fact very few pieces (<10) were badly distorted. Slow air-drying with weighted stacks and horticultural net was used during the dry North-Westerly winds in Canterbury. Further, the air-dried timber was dressed from nominal green 100x40 mm to 90x35 mm which may have removed some of the twist from the dried boards.

Cown (1992b) notes that there is evidence that spiral grain contributes significantly to the economic of processing, i.e. its presence lowers the value of timber. Hasslet *et al.* (1991) estimated that excessive twist reduces the value of timber by $40/cu.m, so with sawn timber production in excess of 2 million cu.m /year spiral grain is a significant problem.

10.3 **COMPRESSION WOOD**

10.3.1 **Test specimens**

It was discussed earlier (Chapter 3) that one of the objectives of the experiment with the small, short internodal top logs was to identify, physically segregate and determine the physical and mechanical properties of compression wood, opposite wood and normal wood separately.

From the 48 internodal top logs a total of 320 clearwood specimens were cut. Of these 126 were normal wood, 107 compression wood and 87 opposite wood.

10.3.2 **Results**

All values of modulus of elasticity, bending strength and density, sorted according to normal wood, compression wood and opposite wood are presented in Appendix 2C. The results of mean modulus of elasticity, bending strength and density based on the three wood types are summarised in Table 10.4.

Table 10.4 **Summary of mean modulus of elasticity (MOE), bending strength (MOR) and density based on the three wood types: data from internodal top logs.**

Wood type	N	MOE (GPa)	MOR (MPa)	Density (kg/cu.m)
Opposite wood	87	6.7 (1.9)	55.0 (8.9)	434 (39.6)
Normal wood	126	7.6 (1.8)	60.6 (9.8)	447 (41.2)
Compression wood	107	8.1 (1.5)	62.7 (8.8)	452 (38.4)
Total	320	7.5 (1.7)	59.8 (9.7)	445 (40.4)

Value in parenthesis is a standard deviation.

Table 8.4 shows that compression wood is superior in all properties while normal wood is intermediate between compression wood and opposite wood.

An analysis of variance test was performed to determine the potentially significant differences between the mean bending strength and modulus of elasticity values of each wood type. The results of the analysis of variance test are summarised in Tables 10.5 and 10.6.

Table 10.5 **Difference comparison between mean bending strength (MOR) values of the three wood types**.

MOR (MPa)	Wood type	Opposite wood	Normal wood	Compression wood
55.0	Opposite wood	-	**	**
60.6	Normal wood	**	-	*
62.7	Compression wood	**	*	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

Table 10.6 **Difference comparison between mean modulus of elasticity (MOE) values of the three wood types.**

MOE (GPa)	Wood type	Opposite wood	Normal wood	Compression wood
6.7	Opposite wood	-	*	**
7.6	Normal wood	*	-	*
8.1	Compression wood	**	*	-

* = significant at 5 percent level; ** = significant at 1 percent level; ns = not significant

10.3.3 **Discussion**

Results observed in Table 10.4 are in line with the statements of Timell (1986) namely:

> "In many respects normal conifer wood can be regarded as a transition form between opposite wood and compression wood"

In confirmation of the above statement, Timell (1986) made a comparative analysis between the physical and mechanical properties of compression wood, opposite wood and normal wood as follows:

Property	Opposite wood	Normal wood	Compression wood
Growth ring	narrow	intermediate	wide
Prop. of latewood	small	intermediate	very large
Tracheid size	long	intermediate	short
S_2 angle	variable	10 - 30^o	30 - 50^o
S_3 layer	thick	thin	absent
Tensile strength	high	intermediate	low
Compression strength	low	intermediate	high

In all properties listed above, except for microfibril angle in the S_2 layer, normal wood occupies a transitional position between opposite wood and compression wood.

The mean density and bending strength values for compression wood and normal wood (Table 10.4) are compatible with the trends of density and bending strength values for other species reported in the Textbook of Wood Technology (Panshin and de Zeeuw, 1980). It is clearly shown in the textbook that the mean density (i.e. in both green and dry conditions) and mean bending strength (i.e. in the green condition only) for compression wood are superior than that for normal wood in all species. Concerning the mean bending strength in the dry condition, compression wood is stronger in some and weaker in other species. For example, compare the mean bending strength values given (Table 8.2 of the textbook) for Pinus ponderosa and Pinus resinosa at about 12% M.C. For the first specie the mean bending strength of compression wood is 19.0% higher than that of normal wood while for the second the bending strength for normal wood is 2.4% higher than that for compression wood.

Concerning modulus of elasticity, the comparatively highest value (8.1 GPa) for compression wood in Table 10.4 is different from published results for other species. Timell (1986) reports that the mean modulus of elasticity of compression wood is lower than that of normal wood. For example, in Table 7.26 (p. 544) of his book Timell has listed ratios of mean modulus of elasticity of compression wood to that of normal wood in both green and dry conditions for Abies sachalinensis, Picea abies and Pseudotsuga menziesii. In all cases the ratios for mean modulus of elasticity of compression wood to that of normal wood range from 0.42 to 0.86. Moreover, the strong negative correlation between microfibril angle and stiffness is well documented by many authors including Cowdrey and Preston (1966), Cave (1968), Meylan (1972), Bendtsen and Senft (1986) and Cave and Walker (1994). Therefore, in view of the high microfibril angle (30 - 50^{o}) reported by Timell (1986) for compression wood a high stiffness value for this wood should not be expected.

In general, the relatively high stiffness value for compression wood and the small differences in density between opposite wood and compression wood reported in this study (Table 10.4) suggests that compression wood was not severe in the short internodal top log.

10.4 TREE VOLUME

10.4.1 Background

There is not much evidence in the literature which directly addresses the impacts of tree volume on the mechanical properties of radiata pine. However, Kloot (1952) examined the effect of rate of growth on the tensile strength and compression parallel to the grain strength in 0.08 mm thick micro-specimens. The samples were cut from two 15-year-old plantation grown radiata pine trees in Australia. Of these two trees, one was fast-grown and the other suppressed, growing in the same plantation and within about 20 yards of one another. He observed that the values for the suppressed tree were superior by about 1.35 times in tensile strength and 1.4 times in compression strength compared with those for the fast-grown tree.

However, in reference to a very slow-grown and moderate grown trees, Findlay (1975, p.46) made a general statement:

> " Wood stripped from the very slow-grown pine and spruce from Archangel is not so strong as that from trees of a moderate rate of growth, and its very fine structure makes it more suitable for joinery than for structural purposes".

Regarding density, Harris *et al.* (1976) stated:

> "There is a negative environment and genetic correlation between growth rate and density which makes it difficult, but not impossible, to optimise volume and wood density production simultaneously. Selection indices based on volume, stem straightness, branch cluster number, and density, achieved good gains simultaneously in volume and straightness, but not in density without sacrificing some gain in volume...The main argument against applying wood density criteria to select families in P.radiata progeny tests is that this would militate against maximising volume production. These grounds for objection require careful scrutiny, including evaluation under specific regimes where there is opportunity for silvicultural selection based on vigour".

More recently, Cown *et al.* (1991a) examined the relationship between tree size and wood density of radiata pine from a number of sites throughout New Zealand. They reported that of 168 correlations they tried, only 41 (24%) proved to be statistically significant at 5% significant level. Among these 41 correlations 32 (78%) were negatively correlated. From this they deduced that there is an overall tendency towards an inverse relationship between ring width and density. Also, they added that their finding was most apparent on high- and medium-density sites.

The above finding indicates that volume has a negative correlation with density of radiata pine. The objective of this section is to examine whether tree volume has any clear relationship with density, stiffness and strength.

10.4.2 **Results and discussion**

A summary of the volume of all the 48 trees with the respective values of mean density and modulus of elasticity and tensile strength for graded boards, and density, modulus of elasticity and bending strength for clearwood specimens is presented in Appendix 3.

The relationships between volume and density, modulus of elasticity and bending strength are plotted in Figures 10.2a - c. Linear regression analysis shows that there is no significant relationship between tree volume and these wood properties. For example, only about 5% (R^2 = 0.05) of the variation in density and bending strength can be explained by tree volume, 1% (R^2 = 0.01) of the variation in modulus of elasticity, and no correlation ((R^2 = 0) with tensile strength.

In order to clarify the implication of the above analysis (which is similar to the procedures used for spiral grain), all the values of density, tensile strength, bending strength and modulus of elasticity of the 48 trees were sorted according to tree volume. It can be seen from Appendix 3 that the minimum and maximum values of tree volume are 0.32 cu.m and 0.60 cu.m respectively. On the basis of this range the 48 data points were divided into four 0.1-cu.m volume classes, with each data point for density, strength and stiffness being grouped into one of these classes according to tree size. A summary of mean density, tensile strength, bending strength and

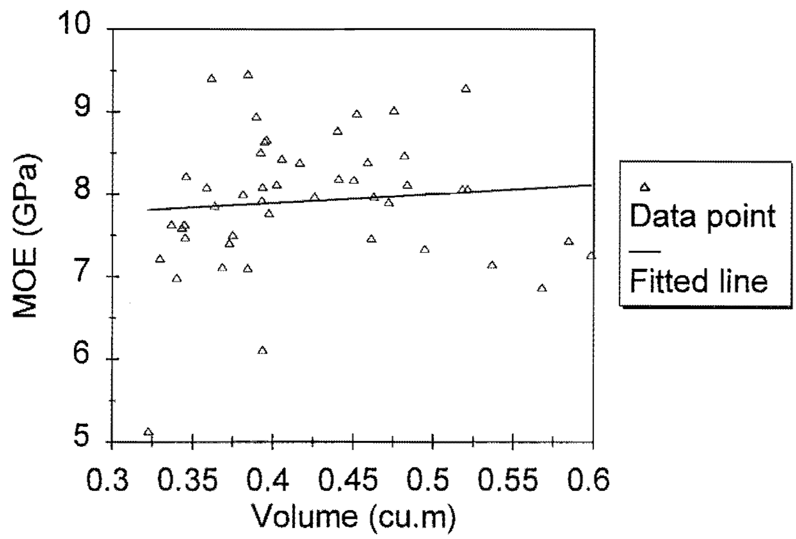


Figure 10.2a Stiffness versus tree volume.

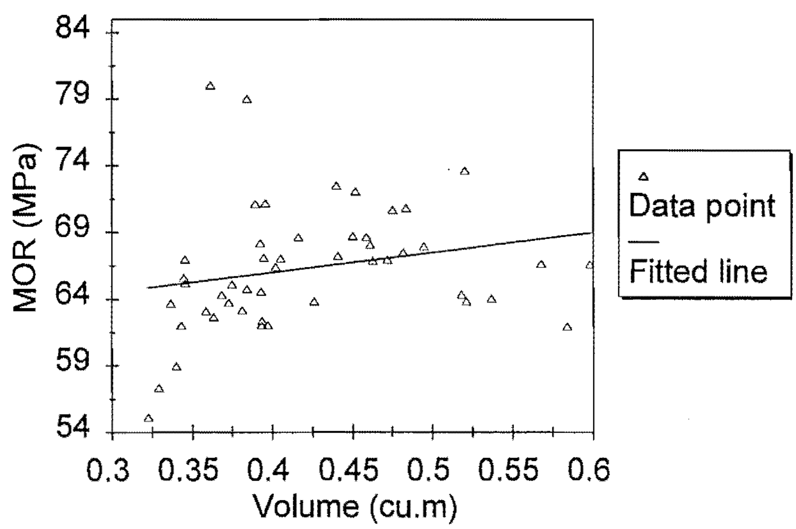


Figure 10.2b Bending strength versus tree volume.

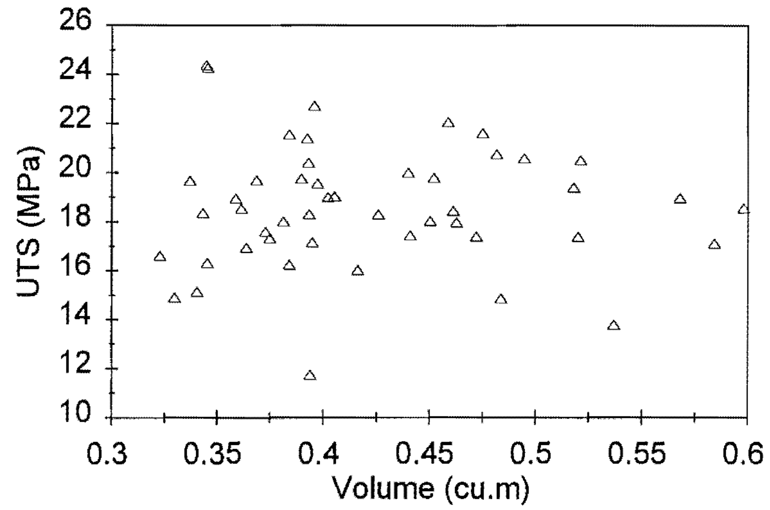


Figure 10.2c Tensile strength versus tree volume.

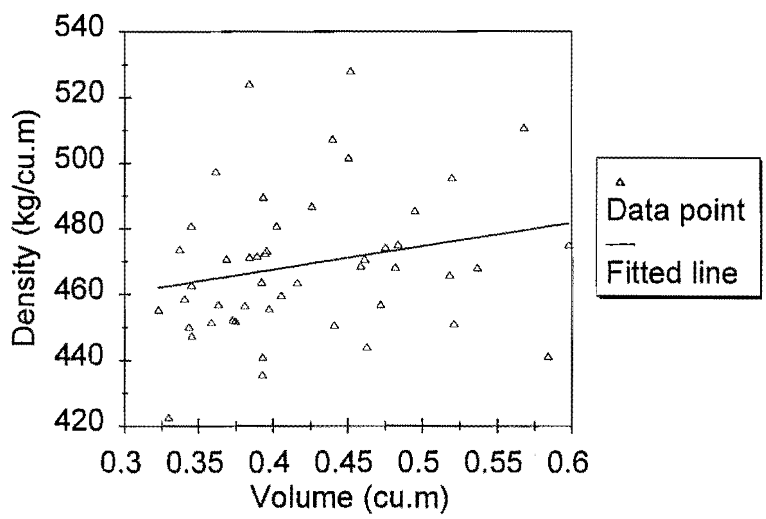


Figure 10.2d Density versus tree volume.

stiffness values, sorted according to the 4 volume classes is presented in Table 10.7

Table 10.7 **A summary of mean density, ultimate tensile strength (UTS), bending strength (MOR) and modulus of elasticity (MOE) values, sorted according to volume classes.**

Volume class (cu.m)	N	MOE* (GPa)	UTS (MPa)	MOR (MPa)	Density* (kg/cu.m)
0.30 - 0.39	5	6.9 (1.0)	16.9 (2.1)	59.4 (3.5)	452 (18.6)
0.40 - 0.49	26	8.1 (0.7)	18.9 (2.7)	66.8 (4.7)	468 (20.6)
0.50 - 0.59	14	8.2 (0.6)	18.8 (2.4)	68.1 (2.9)	475 (21.7)
0.60^{+}	3	7.2	18.2	65.0	476
All	48	7.8 (0.8)	18.6 (2.5)	65.6 (4.7)	467 (22.0)

Value in parenthesis is a standard deviation.
*The modulus of elasticity and density values are from clearwood data.

Table 10.7 shows that the mean values of all properties increase with increasing tree volume.

Low correlations are to be expected (Cown *et al.* 1991a), but it is reassuring to observe small positive regressions between growth rate and stiffness, strength and density. This implies that at worst the penalty in terms of reduced volume is likely to be small were selection made for increased stiffness, strength or density.

CHAPTER 11: **CONCLUSIONS; FUTURE WORK; OPPORTUNITIES**

11.1 **CONCLUSIONS**

The conclusions for the main findings of this study can be summarised under the following sub-topics:

1. Effects of vertical and radial positions within a tree;
2. Stiffness, not density for sorting trees and selecting superior material;
3. Clearwood versus in-grade properties; and
4. Quality improvement of sawmill production.

1. <u>Effects of vertical and radial positions within a tree</u>

Variations in wood quality of any species can be attributed to variations within a tree, between trees in a particular stand, between different growing sites and between different silvicultural regimes. This study has examined differences in the physical and mechanical properties of in-grade timber and clearwood cut from various log types (butt to top log) and various positions from pith to the cambium for trees from a single stand of radiata pine. The conclusions of the two experiments regarding this issue can be summarised as follows:

a. With changes in vertical position up the height of the tree the results show that:

(i) the mean tensile strength, compression strength and bending strength decrease steadily up the tree, i.e. from the butt log to the top log;

(ii) there is only a small decrease in the mean density in moving from the butt log to the top log; and

(iii) the mean modulus of elasticity is roughly constant up the height of the tree; a result which might be a surprise in view of the increasing preponderance of corewood and the decline in the values of all other measured characteristics;

b. With changes in radial position across the diameter of the tree the results show that: with regard to density, stiffness and strength;

(i) all properties increase from the pith outwards;

(ii) the rate of increase is larger near the pith than in the rest of the tree, for all log types and all properties;

(iii) if all boards containing pith material are removed, both the 5%-ile strength and mean stiffness increase by 9%; and

(iv) if all boards closer than 50 mm to the pith are removed, the 5%-ile strength and mean stiffness increase by 16% and 15% respectively.

2. <u>Stiffness, not density for sorting trees and selecting superior material</u>

With reference to the production of structural framing timber, stiffness and density were compared as criteria for sorting trees and identifying superior material within logs, and to determining the improvement in the grade outturn that would arise from the selection of superior trees. The conclusions are summarised as follows:

a. **Stiffness is better than density for selecting superior (stronger and stiffer) trees within the natural population of a forest stand.**

The between-tree variation is such that selection on the basis of stiffness yields trees having at least 25% greater mean stiffness and mean strength compared to the mean values for the original population. However, ranking of trees according to density gives only a modest increase in stiffness (<5%) and strength (<15%);

b. **When selecting trees to improve the value of mill production, the improvement in machine stress grade outturn is much greater when selecting trees for stiffness than when selecting by density.**

c. **If timber is selected on the basis of stiffness (machine stress grading), there**

will be a similar grade outturn from all heights in the tree because both the in-grade and clearwood tests have shown that the middle and top logs are as stiff as the butt logs.

3. <u>Clearwood versus in-grade properties</u>

a. A comparison of in-grade timber (Experiment I) and clearwood (Experiment II) shows that:

(i) the mean modulus of elasticity of the in-grade timber is 86% of the modulus of elasticity of clearwood;

(ii) the mean tensile strength of the in-grade timber is 28% of the mean bending strength of clearwood; and

(iii) the mean density of the in-grade timber is similar to the mean density of the clearwood.

As density was determined on clearwood samples in both experiments the close correspondence in that particular case is to be expected.

b. Regression analysis shows that there is:

(i) a strong relationship (R^2 = 0.76) between the stiffness of in-grade timber and the stiffness of clearwood;

(ii) a strong relationship (R^2 = 0.71) between the density of clearwood cut from the in-grade timber and the density of small clearwood specimens cut from elsewhere in each board.

The regression between the density of clearwood and the in-grade timber is not as high as expected; this may be due to the fact that the measured specimens came from different locations in each board.

(iii) a poor relationship (R^2 = 0.25) between the compression strength of in-grade timber and the compression strength of clearwood.

(iv) a very poor relationship (R^2 = 0.05) between the tensile strength of timber and the bending strength of clearwood.

The poor regression between the tensile strength of timber and bending strength of clearwood, and that between the compression strength of timber and that of clearwood are fully in accordance with early studies by Madsen (1984), who observed that the failure strength of knotty timber is by brittle fracture in the tensile zone whereas clearwood fails in bending by crushing in the compression zone; since the failure modes are unrelated a correlation between the two materials should not be expected. In compression clearwood fails by the buckling of individual cells over the cross section while timber involves crushing of wood cells perpendicular to the grain.

4. <u>Quality improvement of sawmill production</u>

This study investigated three alternative strategies for increasing the quality of sawmill production by removing low grade material. The three alternative strategies were (1) removal of material from near the pith, (2) removal of low stiffness material and (3) removal of material with large knots (visual grading). The conclusions are:

(a) The improvement in stiffness achieved by removing the low stiffness boards was much better than board location or visual grading; and

(b) Visual grading produced a much better improved strength than the other two strategies.

11.2 FUTURE WORK

The following proposals outline the plans for future work:

This study and previous studies at FRI and the University of Canterbury have identified low stiffness to be the principal constraint to the greater use of radiata pine for structural purposes. The strong regression (R^2 = 0.76) reported here between the stiffness of timber and clearwood can be used for subsequent in-depth studies into identifying the fundamental parameters which most influence stiffness. This Ph.D study is only part of a large on-going programme. Future research will focus on the following:

a. Intrinsic stiffness, density and spiral grain will be determined on micro-specimens (1x1x4 mm) of clearwood. Both earlywood and latewood material will be tested separately;

b. Corresponding wood quality characteristics such as compression wood, chemical composition, cellulose quality and quantity and microfibril angle will be examined using the same micro-specimens.

These final tests complete the hierarchical study of Canterbury timber. Thus links will be established between properties of trees, logs, boards, clearwood, "matchstick" and then to intrinsic wood quality characteristics (Figure 11.1).

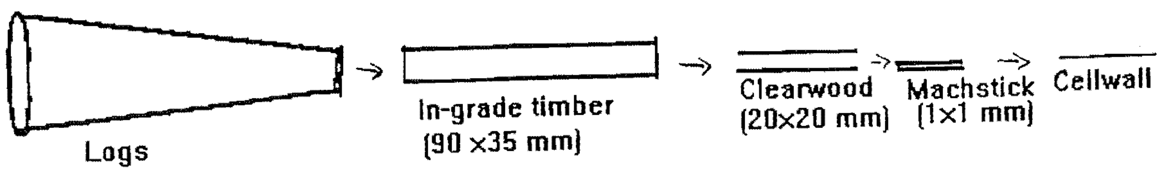


Figure 11.1 **The hierarchical study of Canterbury grown radiata pine timber.**

Only when this study is completed, can variations in mechanical properties of timber both between and within individual trees be related to wood quality aspects (compression wood, density lignin and cellulose content, width of cellulose crystallites, microfibril angle, spiral grain). Testing of matchsticks will complete the causal connections between the mechanical properties of timber and both intrinsic properties of clearwood and the fundamental cell wall characteristics.

Stiffness, strength and wood quality characteristics (i.e. compression wood, chemical characteristics, microfibril angle and spiral grain) will be measured in matchsticks cut from small clearwood (20x20 mm) specimens already selected from those trees which displayed the extremes in intrinsic stiffness. The significance of the chemical and anatomical parameters on stiffness will be determined using a principal component regression analysis.

As can be seen the unique aspect of the research proposal is the matching of intra- and inter-ring density profiles and other wood quality characteristics with the mechanical properties of sawn timber and clearwood, so that a strategy for genetic improvement can be developed.

11.3 OPPORTUNITIES

The traditional approach to improving wood quality has been to argue in favour of selection on the basis of density. However, ranking of trees according to density and stiffness in this study has shown that density does not give as good a prediction of tensile strength or machine stress grade as ranking according to stiffness.

If machine stress grade is the most important indicator of wood value (as in structural engineering), then trees should be bred for stiffness not density. Therefore, some means of *in situ* stiffness measurement would be of a great benefit:

a. during tree breeding in the nursery;

b. in young trees when deciding which trees to cull during thinning operations;

c. at the skids for making decision on log allocation to structural, utility or cut-stock mills or pulp wood.

This overall programme develops a comprehensive research strategy and offer the prospect of opportunities of apply the results in future tree breeding and current machine stress grading operations.

REFERENCES

Addis Tsehaye (1989). Proof testing of juvenile wood. M.For.Sc. thesis, University of Canterbury.

Addis Tsehaye, Buchanan, A.H and Walker, J.C.F. (1992). The strength of finger jointed boxed-pith timber of Pinus radiata. J. Inst. Wood Sci. 12(5): 285-9.

Aldridge, F. and Hudson, R.H. (1958). Growing quality of softwoods: Variation in strength and density of Picea abies. Quarterly Journal of Forestry 52(2): 107-14.

ASTM (1983). Methods of testing small clear specimens of timber (ASTM D:143-52). Philadelphia, PA.

Armstrong, F.H. (1955). The strength properties of wood. For. Prod. Research, Dept. of Scientific and Industrial Research, London. Bull. No. 34.

Armstrong, F.H. (1960). The strength properties of wood. For. Prod. Research, Dept. of Scientific and Industrial Research, London. Bull. No. 45.

Anton, A. (1979). The grading of 13-year-old radiata pine. Proc. of 19th For. Prod. Conf., Melbourne. Paper 2/9.

Austin, S.F. (1988). Quality yield of lumber and plywood produced from fast grown, short rotation Southern pine trees. School of Forestry, State Univ. Nacogdoches, Texas.

Bannister, M.H. (1973). The origin of radiata pine in cultivation. New Zealand For. Service. Government Printer, Wellington, 123 p.

Bendtsen, B.A. (1978). Properties of wood from improved and intensively managed trees. For. Prod. J. 28(10): 61-72.

Bendtsen, B.A. (1985). Quality impacts of the changing timber resource on solid wood products. Proc. 47349, "Managing and marketing the changing timber resource", a conference sponsored by the For. Prod. Research Society. Fort Worth, TX. March 1986.

Bendtsen, B.A. and Senft, J. (1986). Mechanical and anatomical properties in individual growth rings of plantation grown Eastern cotton wood and Loblolly pine. Wood and Fibre Sci. 18(1): 23-38.

Bier, H. (1984). Derivation of timber design stress in New Zealand. Proc. of Pacific Timber Engineering Conference, Vol.3: Wood Science, p. 760-767.

Bier, H. (1985). Structural timber from New Zealand forests. Report Vol. 3: 24-25.

Bier, H. and Collins, M.J. (1985). Bending properties of 100x50 mm structural timber from a 28-year-old stand of New Zealand radiata pine. N.Z Journal of Timber Construction 1(3): 13-20.

Bisset, I.J.W., Dadswell, H.E. and Wardrop, B.A. (1951). Australian Forestry 15(1): 17-30.

Bolden, S, Walsh, R., Grant, D., Leicester, R.H., Young, F. and Seath, C. (1994). In-grade evaluation of Australian pine. Proc. of Pacific Timber Engineering Conf., Gold Coast, Australia. Vol. 2: 716-724.

Booker, R.E. (1987). A method for recording annual ring orientation in boards. For. Prod. J. 37(6): 31-33.

Boone, R.S. and Chundof, M. (1972). Compression wood formation and other characteristics of plantation-grown Pinus caribbea. USDA For. Serv. Res. Pap. ITF - 13. Inst. Trop. Forestry, Puerto Rica.

BS (1957). Methods of testing small clear specimens of wood (BS 373: 1957). British Standards Institution.

Brown, L. (1993). The new shorter Oxford English Dictionary. On historical principles. Vol. 1: A-M. Clarendon Press, Oxford.

Buchanan, A.H. (1986). Radiata pine timber. Grading and testing for structural uses. New Zealand J. of Timber Construction 2(2): 16-24.

Buchanan, A.H. (1989). The bending strength of lumber. J. of Structural Engineering 116(5): 1213-29.

Buchanan, A.H. (1990). The bending strength of lumber. J. Structural Eng. ASCE, N.Y. 116(5): 1213-29.

Burdon, R.D. (1975). Compression wood in P.radiata clones on four different sites. N.Z J. of For. Sci., 5(2): 152-64.

Burdon, R.D. and Bannister, M.H. (1973). Provenances of Pinus radiata: their early performance and silvicultural potential. New Zealand J. of For. 18(2): 217-32.

Cave, I.D. (1968). Anisotropic elasticity of the plant cell wall. Wood Sci. and Tech. 2(4): 268-78.

Cave, I.D. (1969). The longitudinal Young's modulus of Pinus radiata. Wood Sci. and Technol. 3(1): 40-8.

Cave, I.D. and Walker, J.C.F. (1994). Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. For. Prod. J. 44(5): 43-8.

Cowdrey, D.R. and Preston, R.D. (1966). Elasticity and microfibrilar angle in the wood of Sitka spruce. Proc. Roy. Soc. London. 1004: 245-72.

Cown, D.J. (1974). Wood density of radiata pine: its variation and manipulation. New Zealand J. For. Sci. 19(1): 84-92.

Cown, D.J. (1980). Radiata pine: wood age and wood property concepts. NZ J. For. Sci. 10(3): 504-7.

Cown, D.J. (1992a). Corewood (juvenile wood) in P.radiata - should we be concerned? New Zealand J. of For. Sci. 22(1): 87-95.

Cown, D.J. (1992b). New Zealand radiata pine and Douglas fir: Suitability for processing. New Zealand Ministry of Forestry, FRI Bulletin No.168.

Cown, D.J. and Hutchison, J.D. (1983). Wood density as an indicator of the bending properties of Pinus radiata poles. N.Z Journal of Forestry Sci. 13(1):87-99.

Cown, D.J. and Kibblewhite, R.P. (1980). Effects of wood quality variation in New Zealand radiata pine on kraft paper properties. N.Z J. For. Sci. 10: 521-30.

Cown, D.J. and McConchie, D.L. (1980). Wood property variation in an old-crop stand of radiata pine. N.Z. J. For. Sci. 10(3): 508-20.

Cown, D.J. and McConchie, D.L. (1981). Effects of thinning and fertilizer application on wood properties of Pinus radiata. N.Z. J. For. Sci. 11: 79 -81.

Cown, D.J. and McConchie, D.L. (1983). Radiata pine wood properties survey (1977 - 82). New Zealand For. Serv., FRI Bull. No. 50, Rotorua.

Cown, D.J. and McConchie, D.L. (1984). Studies on the intrinsic properties of new-crop radiata pine II: Wood characteristics of 10 trees from a 34-year-old stand grown in Central North Island. FRI Bull. No. 80, For. Research Ins., Rotorua.

Cown, D.J., McConchie, D.L. and Young, G.D. (1991a). Radiata pine wood properties survey. FRI Bull. No.50 (Revised), For. Res. Inst., Rotorua.

Cown, D.J., Young, G.D. and Kimberley, M.O. (1991b). Spiral grain patterns in plantation grown Pinus radiata. NZ J. For. Sci. 21(2/3): 206-16.

Dadswell, H.E., Fielding, M.J., Nichols, P.W.J. and Brown, G.A. (1961). Tree-to-tree variations and the gross heritability of wood characteristics of P. radiata. Tappi 44(3): 174-79.

Dadswell, H.E. and Wardrop, A.B. (1959). Growing trees with properties desirable for paper manufacture. Appita 12(4): 129-36.

Dinwoodie, J.M. (1981). Timber: Its nature and behaviour. Van Nostrand Reinhold, New York.

Domio, L. (1984). What is wood? Tech. Pap. 38 Dept. For. Queensland, Australia.

Donaldson, L.A. (1992). Within- and between-tree variation in microfibril angle in Pinus radiata. N.Z J. For. Sci. 22(1): 77-86.

Doyle, D.V. and Markwardt, L.J. (1967). Tension parallel to the grain properties of southern pine dimension lumber. Res. Pap. FPL84. USDA, Forest Service, Forest Prod. Lab., Madison, WI.

Dutoit, A. J. (1963). A study of the influence of compression wood on the warping of Pinus radiata. South African J. No. 44: 11-15.

European Design Code (1993). Characteristic Stresses for Mechanically Graded Timber, PREN338: Poplar and softwoods species. TRADA, Hughenden Valley, High Wycombe.

Findlay, W.P.K. (1975). Timber properties and uses. Crosby Lockwood Staples, London.

Gerhards, C.C. (1979). Effect of high temperature drying on tensile strength of Douglas fir 2 by 4's. For. Prod. J. 29(3): 39-46.

Green, D.W. and Kretschmann, D.E. (1991). Lumber property relationship for engineering design standards. Wood and Fiber Sci.Vol.? 23 (3), 1991, pp 436-456

Hadi, P. (1992). Proof testing of radiata pine boxed-pith timber. M.For.Sc. thesis, University of Canterbury.

Haght, E.A. Jr (1958). Further study of compression wood in loblolly pine. Forest tree improvement programme, School For. NC State Coll Raleigh, 2nd Rep, 7 pp.

Harris, J.M. (1965). A survey of wood density, tracheid length and latewood characteristics of radiata pine grown in New Zealand. Tech. Pap. For. Res. Inst. N.Z. For. Serv. No. 47. pp 31.

Harris, J.M. (1966). The wood density and tracheid length of young radiata pine trees selected for propagation by cuttings. New Zealand For. Serv., FRI For. Prod. Reprint 201 (unpublished).

Harris, J.M. (1969). The use of beta rays in determining wood properties: Part 3, measuring earlywood and latewood. N.Z J. Sci., 12(2): 409-18.

Harris, J.M. (1973). The use of beta rays to examine wood density of tropical pines in Malaysia, in selection and tree breeding to improve some tropical conifers (eds J. Burley and D.G Nikles), Vol. 2, Commonwealth For. Inst. Oxford, pp. 86-94.

Harris, J.M. (1975). Better wood from better trees. What's New in Forest Research No.30. New Zealand For. Serv., FRI, Rotorua.

Harris, J. M. (1977). Shrinkage and density of radiata pine compression wood in relation to its anatomy and mode of formation. New Zealand J. For. Sci. 7(1): 91-106.

Harris, J.M. (1978). Non-destructive assessment of spiral grain in radiata pine. New Zealand For. Serv., FRI, Wood quality No.23. (unpublished).

Harris, J.M. (1981). Wood quality of radiata pine. Appita 35(3): 211-215.

Harris, J.M. (1989). Spiral grain and wave phenomena in wood formation. Springer-Verlag, Berlin.

Harris, J.M., James, N.R. and Collins, J.M. (1976). Case for improving wood density in radiata pine. N.Z. J. of For. Sci. 5(3): 347-54.

Harris, J. M. and Meylan, B.A. (1965). The influence of microfibril angle on longitudinal and tangential shrinkage in P.radiata. Holzforschung 19: 144-53.

Haslett, A.N., Simpson, I.G. and Kimberley, M.O. (1991). Utilisation of 25-year-old Pinus radiata. Part 2: Warp of structural timber in drying. N.Z. J.For.Sci. 21(2/3): 228-34.

Hiller, C.H. (1964). Correlation of fibril angle with wall thickness in summerwood of slash and loblolly pine. Tappi 47: 125-28.

Hong, K.J. and Wang, S.Y. (1988). Variation in the fundamental wood properties of Taiwan red cypress. Quarterly J. of the Experimental Forest of National Taiwan University. 2(1): 85-100.

Isebrands, G.J. and Huns, M.C. (1975). Growth and wood properties of rapid grown Japanese larch. Wood and Fibre 7(2): 119-28.

Keating, W.G. (1983). Property needs for the wood user. IUFRO Conf. Div. 5 Madison, Wisconsin, 81-94.

Kininmonth, J.A. and Whitehouse, L.J. (1991). Log quality, in properties and uses of New Zealand radiata pine. Volume one: Wood properties. FRI, Rotorua.

Kloot, N. H. (1952). A micro-testing technique for wood. Australian J. Applied Sci. 3(2): 125-43.

Kloot, N.H. (1957). Can the strength of radiata pine be improved? For. Prod. Newsletter No. 232. Timber Mechanics Section, CSIRO, Melbourne.

Koch, P. (1966). Straight studs from Southern pine veneer cores USDA For. Serv. Res. Pap. So-25, 35pp. Southern For. Exp. Station, New Orleans.

Kretschmann, D.E. and Bendtsen, B.A. (1992). Ultimate tensile stress and modulus of elasticity of fast-grown plantation Loblolly pine lumber. Wood and Fiber Sci. 24(2): 189-203.

Langlands, I. (1938). The mechanical properties of South Australian plantation grown P. radiata D. Don. Tech. Pap. No. 30, Division of Forest Products, Commonwealth of Australia Council for Scientific and Industrial Research.

Larson, P.R. (1969). Wood formation and the concept of wood quality. Yale Univ. Sch. For. Bull. No. 74, 54 pp.

Lavers, G.M. (1967). The strength properties of timbers. Bull. No. 50. For. Prod.

Research Pap. So-25, 35 pp. Southern Forest Exp. Station, New Orleans.

Lawrence, M.E. (1988). Stand growth modelling coopperative report No.8 Ministry of Foretry (unpublished).

Madsen, B. (1975). Structural wood and "limit states design". Dept. of Civil Engineering, Univ. of British Columbia. Vancouver, B.C.

Madsen, B. (1976). In-grade testing, degree of damage due to proof loading of lumber in bending. Univ. of British Columbia Dept. of Civil engineering. Report No. 17 ISS. N.0318-3378. Vancouver, B.C.

Madsen, B. (1978). In-grade testing, problem analysis. Forest Prod. J. 28(4): 42-50.

Madsen, B. (1984). A design code for contemporary timber engineering and its implications for international timber trade. Proc. of Pacific Timber Engineering Conference, Auckland. Vol. 3: 950-971.

Madsen, B. and Buchanan, A.H. (1986). Size effects in timber explained by a modified weakest link theory. Canadian Journal of Civil Engineering 13(2): 218 -232.

Manwiller, H.G. (1972). Bark and wood properties of spruce. Research Pap. So-78. USDA For. Serv.

McAlister, R.H. and Clark, A.I. (1991). Effect of geographic location and seed source on bending properties of juvenile and mature loblolly pine. For. Prod. J. 41(9): 39-42.

Meylan, B.A. (1972). The influence of microfibril angle on the longitudinal shrinkage - moisture content relationship. Wood Sci. and Tech. 6(4): 293-301.

Meylan, B.A. and Probine, M.C. (1969). Microfibril angle as a parameter in timber quality assessment. For. Prod. J. 19(4): 30-4.

Moody, R.C. (1970). Tensile strength of finger-joints in pith associated and non-pith associated Southern pine lumber. USDA For. Serv. RES. Pap. FPL 138. For. Prod. Lab., Madison, Wisconsin.

FOA (1994). Forestry facts and Figures. New Zealand Forest Owners Association, New Zealand Min. of Forestry. Wellington.

New Zealand Standard (1988). New Zealand Timber Grading Rules, NZS 3631. Standards Association of New Zealand, Wellington.

New Zealand Standard (1993). New Zealand Timber Structures Standard, NZS 3603. Standards Association of New Zealand, Wellington.

Panshin, A.J. and de Zeeuw, C. (1980). Textbook of wood technology. McGraw-Hill Book company. New York.

Pearson, R.G. and Gilmore, R.C. (1971). Characterisation of the strength of juvenile wood of loblolly pine (P. taeda L.). For. Prod. J. 21(1): 23-50.

Pillow, M.Y., Terrell, B.Z. and Hiller, C.H. (1959). Patterns of variation in fibril angles in Loblolly pine. Forest Prod. Lab., For. Serv., U.S Dept. of Agriculture, Maidson, Wisconsin.

Preston, R.D. (1974). The physical biology of plant cells. Chapman and Hall, London.

SAS (1985). SAS procedures guide for personal computers version 6 edition. SAS Institute Inc. Cary. North Carolina.

Senft, J.F., Bendtsen, B.A. and Galligan, W.L. (1985). Weak wood, fast grown trees make problem lumber. J. of For. 83(8): 477-84.

Smith, R.W. and Briggs, D.G. (1986). Juvenile wood: Has it come of age? Proc. of a Cooperative Technical Workshop, Proc 47309. For. Prod. Research Society, Maidson, WI. p. 5 - 9.

Smith, I., Alkan, S. and Chui, Y.H. (1991). Variation of dynamic properties and static bending strength of plantation-grown red pine. J. Inst. Wood Sci. 12(4): 221-224.

Smith, I., Chui, Y.H., Vincente Perez and Alberto Campos (1993). Machine stress grading of Chilean radiata pine lumber. For. Prod. J. Vol?.386 - 390.

Standards Association of Australia (1978a). Rules for Mechanical Stress Grading of Timber, AS 1749. SAA, North Sydney.

Standards Association of Australia (1978b). Specification for Mechanically Stress Graded timber, AS 1748. SAA, North Sydney.

Standards Association of Australia (1988). Timber Structure Code, Part 1 - Design methods, AS 1720-1. SAA, North Sydney.

AS/NZS 4063: 1992. Joint Australian and New Zealand Standard, Timber- Stress Graded - In-grade Strength and Stiffness Evaluation. SAA, North Sydney.

Sunley, J.G. (1965). Working stresses for structural timbers (for visually and mechanically graded material). For. Prod. Research, Dept. of Scientific and Industrial Research, London. Bull. No. 47.

Timell, T.E. (1986). Compression wood in gymnosperms. Springer-Verlag, Berlin, Vol. 1-3.

USDA (1987). Wood Handbook: Wood as an Engineering material. USDA Forest Service, Forest Prod. Lab., Agri. Handb. No.72. Hemisphere Publishing Corporation, N.Y.

Walford, G.B. (1982). Comparison of tensile and bending strength of 100x50 mm radiata pine. New Zealand For. Serv., FRI Bull. No.21. Rotorua.

Walford, G.B. (1985). The mechanical properties of New Zealand grown radiata pine for export to Australia. New Zealand For. Serv., FRI Bulletin No.93.

Walford, G.B. (1991). Mechanical properties. In Kininmonth, J.A and Whitehouse, L.J Properties And Uses Of New Zealand Radiata Pine. Vol. one - Wood properties, Chapter 8. Forest Research Inst., Rotorua.

Walford, G.B. (1994). Preliminary results of an in-grade evaluation of juvenile radiata pine. Proc. of Pacific Timber Engineering Conf., Gold Coast, Australia. Vol. 2: 725-30.

Walker, J.C.F. (1993). Primary wood processing. Principles and practice. Chapman and Hall, London.

Wardrop, A.B. (1948). Tracheid length. Proc. of Ninth Annual Pulp and Paper Res. Conf., 1:62. Division of For. Prod., CSIRO, Australia.

Wardrop, A.B. (1951). Cell wall organisation and the properties of the xylem I. Cell wall and the variation of breaking load in tension of the xylem in conifer stems. Australian J. of Scientific Research Series B. 4(4): 391-415.

Wardrop, A.B. and Preston, R.D. (1950). Biochim. et biophys. Acta. 6(3): 36-47.

Webster, N. and McKechnie, J.L. (1980). Websters New Twentieth Century Dictionary of the English language unabridged. William Collins, 2129 pp.

Wellwood, R.W. and Smith, J.G. (1961). Variation in some important qualities of wood from young Douglas fir and hemlock trees. Res. Pap. 50 Univ. British Columbia Vancouver, Canada, 15 pp.

Whiteside, I.D. (1974). Machine stress grading: an alternative to visual grading of timber for strength. Information Series No.66. N.Z. For. Serv.

Wilson, H.H. (1976). The effect of the gale of August 1975 on forests in Canterbury, N.Z. Journal of Forestry Sci. 21(1): 133-140.

Wu, S.C. and Wang, Y.C. (1988). The wood properties of Acacia mangium and Acacia aurialiformis. Quarterly J. of the Experimental Forest of National Taiwan University. 2(4): 59-88.

Zobel, B.J. and Blair, R. (1976). Wood and pulp properties of juvenile wood and top wood of the Southern pines. Proc. of 8th Cellulose Conf. May 19-23, 1975. Syracuse, N.Y. In Applied Polymer Symp. 28: 421-33.

Zobel, B.J. and van Buijetenen, J.P. (1989). Wood variation: Its causes and control. Springer Verlag, Berlin.

Zobel, B.J., Kellison, R.C., Mathias, M.F. and Hatcher, A.V. (1972). Wood density of the southern pines. Tech. Bull. No. 208. North Carolina Agri. Exp. Sta. Raleigh, North Carolina, 56 pp.

APPENDICES

APPENDIX 1A: RESULTS OF MODULUS OF ELASTICITY, TENSILE STRENGTH AND DENSITY FOR ALL THE IN-GRADE TIMBER.

Sample No.	Tree No.	Log Type	Position relative to the pith	Distance from Pith (mm)	Grade MSG	Visual Grade	Density (kg/cu.m)	MOE (GPa) in Bending	MOE (GPa) in Tension	UTS (MPa)
1	45	T	2	60	F5	F1	400.07	6.12	6.44	18.57
2	45	T	1	40	F4	B	395.48	4.45	4.36	8.85
3	45	T	1	20	F4	B	462.25	4.07	3.74	9.72
4	45	T	2	40	F4	B	426.56	4.86	5.07	9.61
5	45	T	3	100	F5	F1	435.09	9.04	14.17	20.73
6	45	T	2	60	F5	B	455.31	5.92	5.56	7.23
7	45	T	3	85	F5	F1	464.83	7.50	6.85	12.63
8	33	T	3	90	F5	F2	410.61	7.10	3.57	10.04
9	33	T	2	60	F5	F1	442.60	6.92	6.35	14.79
10	33	T	2	50	F4	F1	445.79	5.18	5.18	20.19
11	33	T	1	20	F5	B	413.72	4.57	4.71	10.58
12	33	T	3	100	F5	F1	426.93	6.17	6.09	19.54
13	33	T	2	70	F5	F1	439.60	7.16	6.62	19.22
14	33	T	3	80	F5	F1	420.94	7.94	8.01	14.79
15	33	T	3	100	F5	F1	435.16	7.36	7.35	21.60
16	27	T	1	30	F5	F2	452.80	5.59	5.43	15.01
17	27	T	2	60	F5	F1	480.52	8.02	7.74	22.46
18	27	T	2	60	F4	B	501.07	5.11	5.68	5.72
19	27	T	2	50	F5	F1	443.67	6.83	7.19	17.28
20	27	T	3	65	F5	F2	460.93	8.23	7.77	12.63
21	27	T	2	70	F5	F1	455.32	8.07	7.09	19.54
22	31	M	1	10	F5	B	439.22	5.53	5.48	11.44
23	31	M	2	45	F5	F1	440.43	7.91	7.88	20.30
24	31	M	2	45	F5	F1	555.44	6.10	5.70	20.19
25	31	M	3	110	F8	F1	471.71	8.68	9.88	43.41
26	31	M	3	80	F8	F1	481.67	9.28	9.00	20.30
27	31	M	3	90	F8	F1	468.46	9.38	10.86	26.35
28	10	M	1	35	F5	F1	492.52	5.28	4.89	13.28
29	10	M	2	55	F5	F1	461.25	5.59	6.16	19.43
30	10	M	3	100	F4	B	453.30	8.02	7.77	15.98
31	10	M	2	65	F5	F1	431.96	7.94	7.31	21.70
32	10	M	2	60	F5	F1	442.26	8.15	7.88	22.14
33	10	M	3	80	F8	F2	466.45	9.67	9.60	18.68
34	10	M	2	60	F8	F1	489.79	7.47	7.28	21.06
35	10	M	3	120	F5	F2	500.62	9.28	9.34	10.80
36	23	T	1	10	F5	B	419.53	5.21	5.58	15.55
37	23	T	2	60	F5	F2	467.74	8.07	7.93	16.74
38	23	T	2	60	F5	F2	440.22	6.53	6.91	13.82
39	26	T	2	45	F5	F1	420.61	7.10	6.87	19.76
40	26	T	2	50	F8	F2	455.23	8.97	8.85	12.96
41	26	T	3	70	F5	F1	416.37	7.20	7.62	20.73
42	11	T	2	40	F4	B	416.65	6.77	7.09	18.79

43	11	T	2	40	F5	F1	430.39	5.67	5.07	19.65
44	11	T	1	30	F5	F1	464.01	6.66	6.30	15.87
45	11	T	3	115	F8	F1	528.49	7.40	7.12	27.53
46	11	T	2	55	F5	F1	435.96	7.01	6.79	14.90
47	13	T	2	40	F5	F2	419.42	4.73	4.78	13.71
48	13	T	1	40	F5	F1	423.49	5.25	5.00	9.83
49	13	T	2	55	F5	F1	428.05	6.77	7.52	17.49
50	13	T	2	60	F5	F2	407.22	6.25	6.26	19.54
51	26	T	1	20	F5	F1	463.48	5.23	5.56	18.03
52	24	T	2	55	F8	F1	454.98	9.34	8.80	23.97
53	24	T	1	25	F5	F2	447.73	6.06	5.82	12.74
54	24	T	2	60	F5	F2	507.44	8.73	8.09	16.09
55	24	T	3	90	F8	F1	456.31	9.91	10.92	23.54
56	24	T	3	90	F5	B	492.34	9.34	8.26	14.47
57	24	T	2	55	F8	F1	510.87	10.43	9.15	17.92
58	1	T	2	40	F5	B	428.13	5.11	4.91	12.96
59	1	T	3	75	F8	F1	413.79	11.31	7.46	19.98
60	1	T	1	20	F5	B	526.47	4.88	4.24	5.40
61	1	T	3	70	F5	F1	424.75	7.40	7.52	22.14
62	1	T	2	60	F5	F1	427.96	7.07	7.77	17.17
63	45	M	1	30	F5	F2	407.92	4.42	4.78	15.77
64	45	M	2	50	F5	B	395.53	5.99	5.48	9.93
65	45	M	1	40	F4	B	414.29	4.12	4.50	10.04
66	45	M	2	50	F5	F1	428.57	5.38	5.16	16.30
67	45	M	3	80	F5	F1	484.22	7.36	7.19	24.40
68	45	M	2	50	F5	B	408.64	5.31	5.13	11.12
69	45	M	3	90	F5	F1	452.00	7.91	7.82	20.19
70	45	M	2	60	F5	B	458.61	6.15	5.87	11.23
71	45	M	2	55	F4	B	429.93	6.80	5.83	8.42
72	45	M	3	90	F8	F1	446.77	8.68	8.17	31.75
73	44	T	2	40	F5	B	431.83	7.04	6.18	8.21
74	44	T	3	70	F5	F2	483.42	8.97	7.96	13.28
75	44	T	1	30	F5	B	423.85	5.31	5.10	14.25
76	44	T	2	60	F4	B	426.15	5.88	5.51	8.96
77	44	T	2	55	F5	B	445.71	6.76	5.63	9.72
78	44	T	3	70	F5	B	418.79	7.83	7.73	10.47
79	44	T	2	50	F5	B	466.64	6.80	6.24	9.61
80	19	M	1	55	F4	B	537.92	4.01	4.26	11.23
81	19	M	1	30	F5	B	484.71	5.05	4.63	11.12
82	19	M	3	90	F5	B	461.02	7.04	6.69	10.69
83	19	M	2	65	F5	F2	434.98	4.88	4.97	14.15
84	19	M	2	60	F5	F2	427.89	7.57	7.12	12.74
85	19	M	2	50	F5	B	439.10	5.53	5.54	10.58
86	19	M	2	60	F5	F2	584.83	6.86	6.67	14.04
87	19	M	3	80	F5	F2	443.52	7.71	7.39	15.66
88	19	M	2	65	F5	F2	460.81	6.74	7.31	14.36
89	6	T	2	50	F5	F2	465.47	5.79	5.45	15.23
90	6	T	1	30	F5	F2	505.14	4.57	4.51	13.07
91	6	T	2	50	F5	F1	469.27	5.30	5.07	21.49
92	6	T	2	60	F5	F2	501.13	6.74	5.51	16.09

93	6	T	3	85	F5	F2	490.06	7.29	6.87	13.07
94	21	M	1	0	F5	F2	422.63	5.61	5.87	15.23
95	21	M	2	50	F5	F2	398.67	6.34	6.13	16.52
96	21	M	1	40	F5	F1	426.06	8.27	8.42	25.48
97	21	M	2	70	F8	F1	425.47	9.06	8.55	19.87
98	38	M	1	20	F5	F2	443.00	4.69	4.93	14.36
99	38	M	2	50	F5	F2	457.02	6.55	6.56	13.61
100	38	M	1	40	F5	F1	433.72	5.15	5.25	19.65
101	38	M	3	75	F8	F1	479.48	9.17	9.21	23.43
102	38	M	2	70	F5	F1	532.14	7.40	7.56	23.54
103	38	M	3	70	F5	F1	484.73	8.97	8.05	25.81
104	22	M	1	20	F5	F2	446.90	4.82	4.89	15.87
105	22	M	2	50	F5	F1	484.30	7.01	6.62	27.43
106	22	M	2	60	F5	F1	468.30	7.27	7.56	21.49
107	22	M	3	75	F8	F1	483.98	9.78	9.88	32.83
108	34	M	2	40	F5	B	472.97	5.05	5.37	11.34
109	34	M	1	30	F5	B	438.80	4.76	5.18	11.55
110	34	M	2	60	F5	F2	437.81	6.60	6.23	14.90
111	34	M	3	75	F5	F1	418.69	8.18	8.05	20.30
112	34	M	2	60	F5	F1	427.17	7.64	7.93	21.92
113	33	M	1	20	F5	F2	506.50	5.03	5.10	14.36
114	33	M	2	50	F4	F2	459.31	5.00	5.26	14.69
115	33	M	3	80	F5	F1	441.83	7.64	8.05	17.92
116	33	M	2	55	F5	F1	496.10	6.22	6.00	21.49
117	33	M	2	70	F5	F1	477.26	7.40	7.12	24.30
118	33	M	3	70	F8	F1	447.45	8.27	7.93	19.87
119	33	M	2	70	F5	F1	475.27	7.33	6.84	19.11
120	47	M	1	40	F4	B	479.82	5.06	5.38	9.61
121	47	M	2	50	F5	F2	461.15	6.55	6.66	13.28
122	47	M	3	70	F8	F1	501.39	9.28	8.85	34.34
123	47	M	2	50	F5	B	476.50	7.10	6.79	14.25
124	47	M	3	85	F8	F1	535.72	8.49	7.93	28.83
125	47	M	3	110	F8	F1	499.90	9.50	8.85	23.76
126	47	M	3	100	F8	F1	545.99	9.67	9.15	28.29
127	47	M	3	70	F5	F2	486.10	8.36	8.05	17.38
128	47	M	2	55	F5	F2	517.21	7.91	7.56	13.93
129	6	M	1	35	F4	F2	480.77	4.50	4.63	14.15
130	6	M	2	40	F5	F2	493.76	4.78	4.81	15.87
131	6	M	3	85	F5	F1	531.22	6.10	5.91	20.95
132	6	M	2	45	F5	F2	449.80	4.88	5.10	15.44
133	6	M	3	90	F5	F1	487.26	6.30	7.71	27.10
134	6	M	3	85	F5	F1	492.04	6.92	6.36	27.64
135	6	M	2	60	F5	F1	498.50	6.10	6.30	21.81
136	41	M	1	30	F5	B	454.66	5.61	5.56	13.61
137	41	M	1	30	F4	B	417.36	5.95	6.56	13.50
138	41	M	3	80	F5	B	499.60	8.68	9.16	10.26
139	41	M	2	65	F5	F1	485.42	8.36	8.09	24.62
140	41	M	2	70	F5	F1	483.63	7.98	8.60	17.49
141	9	M	1	30	F5	F2	559.81	4.67	4.63	16.84
142	9	M	1	25	F5	F2	558.80	2.60	6.09	16.30

143	9	M	2	40	F5	F1	400.24	5.90	5.30	11.01
144	9	M	2	55	F4	B	429.98	8.07	7.31	18.57
145	20	M	1	20	F5	F2	430.31	6.80	5.93	15.55
146	20	M	2	40	F5	F2	471.16	5.35	5.16	14.69
147	20	M	2	50	F5	F2	536.15	5.63	6.44	17.82
148	20	M	3	100	F5	F2	459.99	7.61	8.61	19.33
149	20	M	3	60	F5	F1	454.66	8.02	7.31	20.63
150	20	M	4	90	F8	F1	473.45	8.58	8.60	28.94
151	26	M	1	40	F4	B	464.31	4.63	5.25	12.31
152	26	M	2	55	F5	F1	448.44	6.44	6.96	27.64
153	26	M	3	90	F5	F2	464.55	9.06	9.15	15.01
154	26	M	2	50	F5	F2	455.31	5.61	5.48	16.41
155	26	M	3	110	F5	F2	446.23	8.77	8.17	16.74
156	26	M	2	80	F5	F1	447.54	7.29	6.91	19.54
157	26	M	3	110	F5	F2	453.56	8.73	8.47	15.55
158	23	M	1	10	F5	F1	436.07	5.99	6.13	15.66
159	23	M	2	40	F5	F2	394.06	4.88	6.00	14.90
160	23	M	2	55	F5	B	450.39	6.66	6.19	11.23
161	23	M	3	70	F8	F1	470.73	9.44	9.15	25.16
162	23	M	2	70	F5	F1	477.95	8.18	8.09	29.05
163	23	M	2	70	F8	F1	470.38	9.78	10.02	21.92
164	32	M	1	35	F4	B	421.10	4.06	5.16	11.12
165	32	M	2	60	F5	F1	452.39	7.64	5.50	20.09
166	32	M	3	75	F5	F1	446.23	8.63	8.71	27.53
167	32	M	1	40	F5	F2	386.59	4.97	9.77	13.07
168	32	M	2	65	F5	F1	431.09	8.11	7.62	19.76
169	32	M	3	90	F5	F1	457.57	8.02	8.47	22.03
170	28	M	1	25	F4	F1	437.92	4.86	5.26	17.60
171	28	M	2	60	F5	F1	483.32	7.50	7.18	19.43
172	28	M	3	115	F8	F1	532.45	10.78	10.13	28.29
173	28	M	1	30	F5	F1	428.19	5.75	5.62	16.63
174	28	M	3	80	F5	F2	506.54	9.06	8.52	14.69
175	28	M	3	100	F5	F1	482.73	8.77	9.37	28.18
176	28	M	2	50	F8	F1	498.65	10.16	9.60	20.73
177	4	M	1	30	F5	F1	444.93	6.47	5.93	16.20
178	4	M	1	40	F5	F1	325.29	6.17	9.60	19.54
179	4	M	3	90	F8	F1	451.31	9.06	8.85	27.64
180	4	M	2	50	F8	F1	471.08	8.41	7.77	18.36
181	4	M	2	60	F8	F2	448.51	8.23	7.88	15.66
182	4	M	2	70	F8	F1	441.42	7.91	8.61	20.19
183	12	M	1	40	F5	F1	405.23	4.59	5.93	15.77
184	12	M	1	40	F4	F2	388.14	5.42	6.06	12.96
185	12	M	2	70	F5	F1	412.74	6.08	6.30	20.63
186	12	M	2	50	F4	B	382.46	6.27	4.14	11.88
187	40	M	1	20	F5	F2	434.12	6.98	5.91	15.12
188	40	M	3	60	F8	F1	481.53	9.97	9.77	26.35
189	40	M	2	70	F5	F2	445.79	8.49	8.01	14.79
190	40	M	1	30	F5	F1	436.12	4.98	5.32	16.95
191	40	M	2	50	F5	F2	430.55	6.55	6.84	16.84
192	25	M	1	30	F5	B	419.00	5.75	5.54	10.58

193	25	M	2	60	F5	F2	412.63	6.77	6.51	13.61
194	25	M	2	65	F8	F1	414.15	7.91	7.22	14.04
195	25	M	3	100	F8	F2	467.44	8.63	8.27	14.04
196	25	M	2	70	F8	F1	444.85	8.97	7.96	15.23
197	25	M	2	65	F8	F2	438.20	8.58	8.04	10.15
198	16	M	1	10	F5	F1	514.23	4.52	4.54	13.07
199	16	M	2	45	F4	B	421.54	4.94	4.63	8.53
200	16	M	3	70	F4	B	520.29	6.27	5.60	7.34
201	16	M	2	55	F5	F2	421.21	5.95	5.11	12.31
202	16	M	3	65	F5	F2	449.51	6.66	9.31	15.12
203	16	M	2	60	F5	B	470.77	7.27	6.03	8.64
204	5	M	1	30	F5	F2	469.27	4.46	4.68	14.36
205	5	M	2	55	F5	F1	494.03	5.51	5.51	20.52
206	5	M	3	65	F5	F1	486.94	7.43	7.12	19.00
207	5	M	3	110	F8	F1	550.78	10.16	9.95	25.48
208	5	M	1	30	F5	F2	437.22	4.89	4.82	15.23
209	5	M	2	55	F5	F1	448.38	6.66	6.12	17.60
210	5	M	2	70	F5	F1	496.15	6.95	7.66	15.44
211	5	M	2	55	F5	F2	480.69	6.32	6.72	15.33
212	5	M	2	70	F5	F1	465.51	7.53	7.09	15.87
213	5	M	2	70	F5	F1	532.19	7.98	11.95	23.11
214	5	M	3	105	F8	F1	496.07	8.77	8.05	20.52
215	36	M	1	40	F4	B	466.24	4.53	5.98	8.96
216	36	M	2	60	F5	B	477.82	6.20	7.10	11.01
217	36	M	3	95	F8	F2	431.67	8.58	7.98	14.25
218	36	M	2	50	F5	F2	442.81	5.73	5.51	13.28
219	36	M	3	70	F8	F1	439.55	8.54	8.52	14.15
220	36	M	3	70	F5	F2	429.64	8.77	8.34	14.90
221	36	M	2	70	F8	F1	476.58	7.75	8.22	24.40
222	37	M	1	20	F4	B	536.96	4.24	4.55	11.12
223	37	M	2	60	F4	F1	512.16	5.42	5.60	19.33
224	37	M	3	60	F8	F1	512.80	9.12	8.71	23.11
225	37	M	2	45	F5	F1	463.13	5.08	6.24	16.52
226	37	M	2	70	F8	F1	510.65	8.97	9.52	20.52
227	37	M	3	80	F5	F1	467.25	9.06	8.17	22.14
228	37	M	3	90	F8	F1	524.69	9.02	8.85	23.11
229	27	M	2	40	F5	F1	452.62	5.86	6.06	14.15
230	27	M	2	60	F8	F1	444.78	8.58	8.60	14.90
231	27	M	1	35	F5	F2	501.47	5.05	4.93	15.55
232	27	M	2	65	F5	B	508.60	5.97	5.93	22.68
233	27	M	3	80	F8	F1	477.23	9.06	8.85	17.38
234	27	M	3	70	F5	F1	471.39	8.87	8.60	18.03
235	27	M	2	70	F5	F1	459.14	7.83	7.52	16.09
236	11	M	1	30	F5	F2	436.34	5.26	5.10	13.17
237	11	M	2	60	F8	F1	433.60	6.44	7.29	15.01
238	11	M	2	70	F5	F1	458.76	9.92	8.71	14.25
239	11	M	2	55	F5	F1	440.21	7.40	5.56	12.63
240	11	M	3	85	F5	F1	462.47	9.78	9.53	34.88
241	11	M	3	115	F5	F2	425.71	7.75	16.34	17.38
242	18	M	1	40	F4	B	422.08	4.50	4.74	13.82

243	18	M	1	40	F5	B	432.01	5.53	4.35	9.29
244	18	M	3	70	F5	F1	454.23	8.63	8.52	19.00
245	18	M	2	70	F5	B	425.82	5.44	5.19	8.53
246	18	M	3	100	F5	F1	451.64	8.02	7.18	20.30
247	18	M	2	70	F5	F1	451.73	7.79	7.35	26.02
248	18	M	4	110	F8	F1	434.91	8.63	8.39	24.73
249	18	M	2	55	F5	F1	424.51	6.89	6.13	22.78
250	18	M	3	85	F5	B	499.84	8.36	6.02	9.93
251	30	M	1	40	F5	F1	424.56	4.40	4.20	18.79
252	30	M	2	70	F5	F1	408.43	6.47	6.87	20.30
253	30	M	1	30	F5	F2	403.33	5.82	5.64	14.69
254	30	M	2	70	F5	F1	414.67	7.98	8.71	25.05
255	30	M	3	90	F8	F1	468.15	9.97	10.13	25.59
256	15	M	1	15	F5	B	431.60	5.16	5.87	13.17
257	15	M	2	40	F5	F1	421.31	7.10	7.28	18.90
258	15	M	3	110	F8	F1	463.03	9.97	9.70	23.32
259	15	M	2	45	F5	F1	462.20	6.50	7.00	21.38
260	15	M	3	85	F8	F1	477.31	9.44	12.72	27.75
261	15	M	3	75	F8	F1	479.67	9.78	9.77	24.51
262	15	M	2	70	F5	F1	454.97	7.87	7.85	18.68
263	15	M	2	55	F5	F2	438.02	7.79	8.22	15.23
264	15	M	3	100	F8	F1	488.41	9.12	8.21	19.87
265	14	M	1	20	F5	F1	473.22	6.03	4.72	16.20
266	14	M	2	65	F5	B	459.73	4.79	5.76	11.34
267	14	M	2	60	F5	F2	467.00	5.40	6.89	10.90
268	14	M	2	55	F5	B	447.00	6.95	5.72	15.66
269	14	M	2	45	F4	F2	472.72	4.85	5.37	12.20
270	43	M	1	15	F4	B	435.72	4.48	4.59	15.23
271	43	M	2	50	F5	F1	474.47	5.53	5.50	16.41
272	43	M	3	100	F8	F1	482.70	8.41	8.34	17.71
273	43	M	2	45	F5	F1	434.21	6.44	6.99	15.66
274	43	M	3	70	F8	F1	465.04	8.54	8.47	24.83
275	43	M	2	50	F5	F2	488.06	7.43	6.44	12.63
276	48	M	2	50	F5	F1	412.37	6.20	5.91	25.16
277	48	M	3	90	F8	F1	415.44	8.63	8.97	23.22
278	48	M	1	20	F4	F1	402.07	4.40	4.26	17.82
279	48	M	2	55	F5	F2	422.61	5.37	5.67	13.28
280	48	M	2	65	F5	F2	427.54	7.01	6.38	15.12
281	29	M	1	10	F4	B	417.62	4.45	3.79	11.12
282	29	M	2	50	F5	F2	449.40	7.10	6.96	19.33
283	29	M	3	80	F5	F1	466.89	7.61	8.17	22.03
284	29	M	2	50	F5	F1	484.38	6.66	6.51	19.65
285	29	M	3	90	F8	F1	533.17	10.22	10.92	21.60
286	42	M	3	80	F8	F1	497.96	8.18	8.25	21.06
287	42	M	2	60	F5	F2	427.52	7.10	7.00	14.90
288	42	M	1	35	F5	F1	498.92	5.19	5.67	15.77
289	42	M	3	100	F5	F1	455.93	7.01	7.22	15.23
290	42	M	2	60	F5	F1	451.91	6.98	7.09	16.74
291	44	M	1	20	F5	F2	492.34	5.18	5.18	15.77
292	44	M	2	50	F4	B	518.87	5.48	6.32	15.01

293	44	M	3	100	F5	B	473.32	6.29	6.07	13.82
294	44	M	2	50	F5	F2	452.35	6.86	7.57	13.07
295	44	M	2	60	F5	F1	429.62	6.86	7.13	21.81
296	44	M	2	50	F5	B	425.61	5.44	5.94	14.04
297	44	M	3	85	F5	F1	476.84	7.71	7.98	21.49
298	24	M	1	30	F5	B	468.32	6.53	6.33	11.12
299	24	M	2	60	F5	F1	510.12	7.98	8.17	24.30
300	24	M	3	50	F8	F1	520.80	9.06	8.85	25.81
301	24	M	3	70	F8	F1	597.69	10.04	10.21	26.35
302	24	M	2	95	F8	F2	465.11	8.73	8.71	18.14
303	35	M	1	30	F4	B	442.27	4.40	4.78	13.17
304	35	M	2	55	F5	F1	426.54	5.26	5.25	18.68
305	35	M	2	50	F5	F1	434.25	6.37	6.33	15.98
306	35	M	3	80	F8	F1	478.38	8.63	8.77	24.19
307	35	M	3	100	F8	F1	479.35	8.97	8.80	22.24
308	35	M	2	70	F8	F1	465.33	8.36	7.62	20.41
309	35	M	3	95	F8	F1	508.04	8.45	9.31	21.49
310	39	M	1	30	F5	F2	460.09	5.59	5.22	15.87
311	39	M	2	50	F5	F1	455.24	6.74	6.51	16.63
312	39	M	3	90	F8	F1	472.48	9.44	9.53	23.65
313	39	M	3	100	F5	F1	446.73	8.77	9.00	27.64
314	39	M	2	65	F5	F1	432.83	7.64	7.41	22.46
315	39	M	3	70	F8	F1	452.39	9.78	10.21	25.48
316	13	M	1	20	F5	F1	400.90	4.61	5.00	9.83
317	13	M	2	40	F5	F1	402.23	4.85	4.82	14.69
318	13	M	3	100	F5	B	417.42	8.02	7.66	17.92
319	13	M	2	60	F5	F1	421.95	7.53	6.67	17.49
320	13	M	3	100	F8	F1	436.05	8.23	7.22	16.63
321	13	M	2	70	F5	F1	402.74	7.27	7.56	17.06
322	13	M	2	70	F4	B	424.65	7.98	7.41	19.65
323	13	M	3	115	F5	F1	431.35	9.23	9.00	22.68
324	46	M	1	40	F4	B	469.63	4.71	5.03	8.75
325	46	M	2	70	F5	F1	458.59	7.04	7.71	20.73
326	46	M	2	55	F4	B	545.09	5.67	5.12	8.75
327	46	M	1	30	F5	F1	443.96	4.92	5.22	21.06
328	17	M	2	40	F5	F1	421.59	6.37	6.33	19.00
329	17	M	1	10	F4	B	451.30	4.03	4.13	10.04
330	17	M	2	60	F5	F2	402.12	5.09	5.36	15.98
331	17	M	2	70	F8	F2	472.86	8.36	7.52	15.98
332	17	M	2	70	F5	F1	453.30	8.58	7.98	22.35
333	8	M	1	30	F4	B	502.09	6.01	5.45	16.84
334	8	M	2	55	F5	F1	450.66	7.27	7.22	15.66
335	8	M	2	60	F5	F1	508.09	4.18	3.94	9.93
336	8	M	2	55	F5	F1	493.75	8.45	8.43	25.27
337	1	M	2	40	F5	F1	457.87	7.71	7.74	21.27
338	1	M	1	35	F5	F2	472.74	5.88	5.88	14.90
339	1	M	1	25	F5	B	461.74	5.16	5.24	10.04
340	1	M	2	60	F5	B	436.77	8.27	6.20	10.16
341	1	M	2	70	F8	F1	457.90	8.02	8.17	18.14
342	7	M	2	50	F5	F1	482.93	5.71	6.41	16.52

343	7	M	2	65	F5	F2	529.93	9.50	8.47	24.73
344	7	M	1	30	F8	F1	455.31	6.63	5.97	14.04
345	7	M	2	70	F5	F2	463.87	7.43	7.31	19.33
346	2	M	1	20	F5	F1	449.67	4.48	3.22	12.20
347	2	M	2	40	F4	B	435.61	3.71	4.11	14.04
348	2	M	2	45	F4	F1	408.26	5.08	4.34	15.01
349	3	M	1	20	F8	F2	486.64	5.55	5.47	16.09
350	3	M	2	60	F5	F1	518.98	8.45	9.32	20.63
351	3	M	3	130	F11	F1	530.23	12.64	11.95	44.70
352	3	M	1	30	F5	F2	466.80	5.05	4.68	12.20
353	3	M	2	60	F5	F2	473.51	7.13	6.91	12.85
354	3	M	2	65	F5	F1	494.74	9.17	9.00	20.30
355	3	M	2	70	F8	F2	484.93	8.73	8.60	18.36
356	36	B	1	25	F4	B	474.70	4.59	4.51	14.25
357	36	B	2	60	F5	F1	437.86	7.07	6.79	22.03
358	36	B	1	40	F4	F1	499.37	4.35	4.08	17.49
359	36	B	2	60	F5	F1	425.65	6.03	6.23	19.98
360	36	B	3	100	F8	F1	488.03	8.77	8.85	28.94
361	36	B	2	110	F8	F1	476.50	7.98	7.41	35.63
362	36	B	2	70	F5	F2	430.02	7.61	7.12	15.12
363	36	B	2	60	F5	F1	449.16	6.98	6.96	19.76
364	17	B	1	30	F5	B	470.89	4.24	4.58	14.90
365	17	B	3	70	F5	F1	464.50	6.08	6.26	28.40
366	17	B	2	55	F5	F1	492.11	5.23	5.18	13.93
367	17	B	3	70	F5	F1	486.51	8.44	7.77	27.21
368	17	B	3	85	F5	F1	450.74	7.64	8.05	23.65
369	17	B	2	70	F5	F1	467.56	7.16	7.56	22.03
370	15	B	1	35	F4	B	481.60	4.16	3.92	15.87
371	15	B	2	40	F5	B	493.50	4.78	3.93	23.00
372	15	B	3	100	F5	F1	501.83	7.68	8.22	26.78
373	15	B	1	35	F5	F2	475.40	5.25	5.20	15.77
374	15	B	2	70	F5	F2	517.92	8.15	8.17	16.74
375	15	B	3	95	F8	F1	544.65	10.04	9.70	37.79
376	15	B	3	85	F8	F1	531.30	9.34	9.15	36.17
377	15	B	2	70	F5	F1	541.91	7.01	7.66	25.37
378	15	B	2	70	F5	F1	498.68	6.83	6.38	19.76
379	15	B	2	70	F5	F1	509.38	8.58	9.21	29.16
380	46	B	1	30	F4	B	452.45	3.96	4.31	11.34
381	46	B	2	70	F4	F1	473.87	5.79	5.76	18.90
382	46	B	3	90	F8	F1	482.24	9.72	8.66	30.88
383	46	B	1	40	F4	F2	425.85	4.48	4.16	16.84
384	46	B	3	85	F5	F1	457.43	7.98	7.69	24.30
385	46	B	2	70	F5	F1	466.61	7.79	7.05	21.70
386	46	B	2	70	F8	F1	502.58	7.75	7.71	23.32
387	46	B	3	70	F8	F1	496.25	8.77	8.17	31.42
388	38	B	1	20	F4	F2	445.93	4.35	4.08	17.82
389	38	B	2	50	F5	F2	475.30	5.15	5.15	17.60
390	38	B	1	45	F5	F1	444.21	5.03	5.04	20.52
391	38	B	3	90	F5	F1	473.88	8.36	7.93	27.21
392	38	B	2	55	F5	F1	522.22	6.86	6.38	22.57

393	38	B	2	55	F5	F1	477.96	6.80	6.75	17.92
394	4	B	1	20	F5	F2	493.35	4.85	4.54	15.98
395	4	B	2	60	F5	F1	456.11	6.83	6.67	27.32
396	4	B	3	95	F8	F1	521.63	10.29	9.70	19.33
397	4	B	2	50	F5	F1	465.20	5.55	5.37	20.09
398	4	B	3	70	F5	F1	499.06	9.17	9.60	19.11
399	4	B	2	70	F4	F2	487.62	8.32	8.39	20.30
400	4	B	3	70	F8	F1	460.89	9.72	9.31	27.53
401	5	B	1	15	F4	B	493.48	3.81	3.40	10.04
402	5	B	2	45	F4	F2	427.19	4.09	4.10	16.95
403	5	B	3	90	F5	F1	500.16	5.44	5.64	17.06
404	5	B	2	25	F4	F2	523.26	4.12	3.82	17.17
405	5	B	2	65	F5	F1	649.78	5.08	4.69	18.68
406	5	B	4	90	F5	F1	565.28	6.72	9.96	32.07
407	5	B	3	70	F5	F1	507.47	6.80	7.41	20.19
408	5	B	3	90	F5	F1	548.44	7.04	6.12	24.40
409	5	B	3	85	F5	F1	495.47	5.61	5.75	23.86
410	5	B	2	45	F5	F2	490.25	5.37	5.90	14.79
411	5	B	3	70	F5	F1	517.52	6.25	6.75	21.38
412	5	B	4	120	F8	F1	542.06	8.58	8.09	16.63
413	5	B	2	30	F4	F1	568.11	4.36	4.07	17.60
414	13	B	1	45	F5	F2	468.02	3.54	3.53	13.93
415	13	B	2	55	F5	F1	465.48	4.28	4.24	18.68
416	13	B	2	65	F5	F1	450.48	6.27	5.99	13.93
417	13	B	4	125	F5	B	482.12	9.97	9.88	31.53
418	13	B	2	40	F4	F2	404.60	4.59	4.87	16.20
419	13	B	3	120	F8	F1	455.09	7.98	7.88	20.95
420	13	B	1	35	F5	F1	544.17	5.23	5.60	10.26
421	13	B	1	40	F5	B	472.71	6.89	8.47	14.04
422	13	B	3	120	F8	F1	451.43	8.07	7.82	30.13
423	13	B	3	110	F5	F1	532.02	8.11	7.88	29.91
424	13	B	2	70	F5	F2	474.09	8.41	8.26	17.60
425	20	B	1	30	F4	F2	504.82	4.57	5.00	16.63
426	20	B	2	50	F5	F1	482.55	5.63	5.82	18.46
427	20	B	3	90	F8	F1	507.02	9.02	8.60	19.43
428	20	B	2	40	F5	F1	523.70	6.44	5.91	19.54
429	20	B	3	110	F8	F1	502.71	9.38	9.31	44.70
430	20	B	2	70	F5	F1	465.63	7.40	6.71	21.92
431	20	B	2	70	F8	F1	486.83	8.73	7.88	25.27
432	20	B	3	110	F8	F1	541.66	9.44	10.32	26.45
433	20	B	3	100	F8	F1	517.37	9.34	9.00	37.58
434	20	B	4	110	F8	F1	558.01	10.22	11.03	31.64
435	20	B	3	100	F8	F1	514.03	10.29	10.32	19.54
436	10	B	1	40	F5	F2	462.53	4.36	4.05	9.61
437	10	B	2	55	F8	F1	495.09	5.40	5.58	14.15
438	10	B	3	90	F5	F2	509.03	7.50	7.53	12.85
439	10	B	1	40	F8	F2	433.47	5.46	5.05	14.15
440	10	B	2	60	F5	B	503.06	8.32	7.45	14.15
441	10	B	3	55	F8	F2	466.24	6.17	6.62	20.41
442	10	B	2	60	F5	B	521.03	7.01	6.42	7.77

443	10	B	3	115	F8	F1	529.01	8.92	6.75	14.04
444	10	B	3	110	F5	F1	510.74	10.16	9.87	32.50
445	10	B	3	85	F5	B	483.77	8.97	8.94	20.73
446	10	B	3	70	F5	F1	520.20	8.36	7.96	17.71
447	22	B	1	10	F4	F2	497.47	3.96	4.44	17.06
448	22	B	2	30	F4	F2	488.72	4.91	4.74	14.79
449	22	B	3	80	F5	F1	559.56	8.87	8.39	21.81
450	22	B	2	55	F4	F2	488.98	4.60	4.18	15.55
451	22	B	3	90	F5	F1	562.05	8.11	7.82	50.10
452	22	B	2	70	F5	F1	537.36	8.58	8.39	27.10
453	22	B	2	70	F5	F1	542.85	6.53	6.62	28.72
454	33	B	1	40	F5	F2	442.77	4.45	3.53	13.07
455	33	B	2	50	F5	F1	478.69	5.18	5.84	17.71
456	33	B	2	120	F5	F1	474.38	7.40	9.43	43.51
457	33	B	2	45	F5	F1	438.89	5.48	5.48	17.06
458	33	B	3	60	F8	F1	518.54	8.02	8.01	36.17
459	33	B	2	55	F5	F1	449.72	5.88	6.09	19.98
460	33	B	1	45	F5	F1	533.68	4.61	5.53	22.57
461	33	B	3	90	F5	F1	469.89	7.20	6.75	20.30
462	33	B	3	110	F5	F1	492.89	7.27	7.62	28.51
463	33	B	4	115	F8	F1	494.64	9.38	8.85	31.42
464	31	B	1	30	F5	F1	460.14	4.92	4.12	11.23
465	31	B	2	60	F5	F1	478.73	6.15	5.87	20.84
466	31	B	3	90	F8	F1	543.82	8.27	8.82	25.37
467	31	B	2	45	F5	F2	493.55	6.77	6.35	12.74
468	31	B	2	60	F8	F1	504.16	9.02	10.13	35.85
469	31	B	3	100	F8	F1	540.55	9.67	9.31	33.69
470	30	B	1	10	F5	F1	430.27	4.80	4.89	15.66
471	30	B	2	50	F5	F1	438.67	5.33	5.76	17.49
472	30	B	3	110	F5	F2	460.83	8.15	8.94	18.68
473	30	B	2	50	F5	F1	460.67	7.47	7.05	26.24
474	30	B	2	70	F5	F1	452.53	6.37	6.67	30.13
475	30	B	2	60	F5	F1	473.30	7.01	7.77	20.52
476	30	B	3	85	F8	F1	472.69	8.27	9.23	25.91
477	40	B	1	10	F5	F2	455.95	4.78	5.77	12.74
478	40	B	2	65	F5	F1	467.34	7.91	7.71	21.49
479	40	B	1	30	F4	F2	479.88	4.15	4.05	12.63
480	40	B	2	50	F5	F1	466.66	5.51	5.59	18.46
481	40	B	3	100	F8	F1	517.57	10.16	9.77	22.57
482	40	B	2	70	F5	F2	460.56	7.53	7.96	13.17
483	40	B	3	90	F8	F1	467.84	8.63	9.06	24.73
484	42	B	1	40	F4	F2	455.26	4.47	4.29	13.50
485	42	B	1	25	F4	B	448.15	4.57	5.21	12.85
486	42	B	2	65	F5	F2	452.17	6.66	6.71	17.82
487	42	B	1	40	F5	F1	483.98	4.98	4.89	23.86
488	42	B	3	100	F5	F1	517.56	7.20	7.49	17.60
489	42	B	3	90	F5	F2	479.28	7.27	8.80	21.17
490	42	B	2	50	F5	B	477.66	6.58	6.35	11.01
491	42	B	3	60	F5	F1	463.50	7.50	7.88	32.61
492	39	B	2	40	F4	F1	489.92	5.37	5.35	16.30

493	39	B	3	80	F4	F1	499.60	8.87	8.94	27.43
494	39	B	1	35	F5	F1	500.83	4.80	5.18	17.38
495	39	B	2	50	F5	F2	489.15	6.22	4.71	13.07
496	39	B	3	80	F8	F1	517.02	8.82	8.94	29.16
497	39	B	3	70	F8	F1	505.86	8.68	8.60	29.70
498	39	B	2	70	F5	F1	465.83	8.15	8.66	26.13
499	35	B	1	30	F4	F2	502.26	3.89	3.84	17.71
500	35	B	1	30	F5	F1	485.34	4.69	4.43	19.33
501	35	B	3	95	F5	F2	539.89	7.75	8.15	23.86
502	35	B	1	25	F5	F1	323.93	4.86	14.91	18.03
503	35	B	3	80	F8	F1	520.92	9.56	9.77	32.72
504	35	B	3	100	F8	F1	499.48	8.82	9.77	29.26
505	35	B	2	70	F8	F1	502.39	7.98	8.26	33.15
506	35	B	2	70	F8	F1	517.28	8.68	8.94	24.62
507	35	B	2	70	F8	F1	506.02	8.11	8.88	25.91
508	37	B	1	25	F4	B	545.84	3.27	3.20	10.90
509	37	B	1	35	F4	B	553.57	4.04	3.86	13.39
510	37	B	2	60	F5	F2	564.93	6.10	6.30	13.07
511	37	B	1	35	F4	B	488.75	3.71	3.69	9.83
512	37	B	3	90	F5	F2	495.79	7.29	9.61	13.07
513	37	B	3	80	F5	F1	526.81	7.47	9.24	34.77
514	37	B	2	40	F5	F1	517.29	5.42	5.08	19.22
515	37	B	3	100	F5	F1	509.56	6.89	10.02	17.38
516	37	B	4	100	F8	F1	584.92	10.16	10.60	25.48
517	25	B	2	40	F5	F1	418.31	6.83	6.59	18.68
518	25	B	2	70	F8	F1	514.74	9.78	7.57	23.22
519	25	B	1	40	F5	B	459.80	5.67	5.79	10.69
520	25	B	2	50	F5	B	464.26	6.29	6.36	16.20
521	25	B	3	100	F8	F1	530.88	8.68	8.60	27.86
522	25	B	2	60	F5	B	440.89	6.98	9.32	11.34
523	25	B	4	100	F11	F1	468.82	9.85	9.77	30.67
524	25	B	3	110	F8	F1	547.55	9.23	9.00	17.28
525	25	B	4	95	F8	F1	517.22	9.56	9.15	27.21
526	5	T	1	30	F5	F2	477.81	4.67	5.09	17.06
527	5	T	1	30	F5	F1	531.37	5.15	4.97	19.33
528	5	T	2	60	F5	B	521.79	6.47	6.26	13.71
529	5	T	2	50	F5	F1	491.60	5.61	5.93	22.68
530	5	T	2	60	F5	F1	472.71	7.91	8.05	24.08
531	5	T	2	65	F5	F1	499.93	6.58	7.22	22.89
532	5	T	3	70	F8	F1	495.27	7.07	6.71	15.33
533	5	T	3	90	F8	F1	503.24	8.68	8.09	19.11
534	22	T	1	20	F5	F1	447.97	5.30	4.92	18.79
535	22	T	2	65	F5	F1	538.27	8.07	8.01	26.89
536	22	T	2	65	F5	F1	433.79	7.40	7.66	23.22
537	17	T	1	10	F4	B	529.58	4.16	4.34	9.61
538	17	T	2	45	F5	F2	430.79	6.77	6.03	11.34
539	17	T	2	40	F5	F1	407.28	6.32	6.22	17.06
540	17	T	3	80	F8	F1	449.69	8.15	7.98	23.86
541	4	T	1	20	F5	F2	469.46	6.01	6.33	14.15
542	4	T	2	50	F5	F2	460.83	7.27	6.67	11.77

543	4	T	2	50	F5	F1	443.48	6.74	6.62	16.41
544	4	T	2	70	F5	F2	434.38	8.32	8.66	14.15
545	41	T	1	40	F5	B	449.66	5.09	4.98	9.83
546	41	T	2	50	F5	F1	461.33	6.06	5.78	16.95
547	41	T	3	90	F8	F2	489.26	8.63	8.09	15.01
548	41	T	2	50	F5	F2	479.42	7.61	7.22	15.12
549	41	T	2	50	F5	B	460.30	7.40	7.32	14.15
550	43	T	1	20	F5	B	478.36	4.47	4.36	12.42
551	43	T	2	50	F5	F1	437.33	5.95	5.91	17.60
552	43	T	2	50	F5	F1	474.97	5.97	6.30	17.17
553	43	T	3	70	F8	F1	501.32	8.23	8.22	16.74
554	40	T	1	20	F5	B	433.23	5.46	5.94	13.71
555	40	T	2	60	F5	F2	423.20	6.95	6.58	11.23
556	40	T	2	65	F5	F1	440.08	7.43	7.09	14.90
557	40	T	2	60	F5	F2	453.33	6.77	6.16	15.12
558	32	T	1	20	F5	F2	400.75	5.97	5.93	15.66
559	32	T	2	60	F5	F1	478.93	6.80	6.77	19.98
560	32	T	1	40	F4	B	409.67	4.56	5.19	9.83
561	32	T	2	50	F5	F1	433.14	5.38	5.50	22.03
562	32	T	2	60	F5	F1	418.43	6.22	6.67	16.30
563	20	T	1	0	F5	B	455.41	5.40	5.36	8.31
564	20	T	2	60	F5	F2	429.11	6.42	6.26	12.53
565	20	T	2	40	F5	F2	445.86	7.10	6.23	15.44
566	20	T	3	65	F8	F1	472.27	8.77	8.80	20.09
567	20	T	2	60	F5	F1	440.63	7.91	7.82	23.00
568	20	T	2	70	F8	F1	465.49	8.87	8.52	19.87
569	14	T	1	35	F4	B	585.94	5.88	4.68	7.77
570	14	T	1	40	F5	B	506.90	4.86	5.03	10.47
571	14	T	2	40	F4	B	483.76	5.82	4.96	7.56
572	29	T	2	50	F5	B	512.20	6.53	6.64	7.77
573	29	T	2	60	F8	F1	501.61	7.53	7.98	19.76
574	29	T	2	60	F5	F1	465.56	7.64	7.36	13.07
575	29	T	1	30	F5	F2	449.61	7.23	6.99	19.00
576	15	T	1	25	F5	B	420.92	5.06	5.11	10.37
577	15	T	2	60	F5	F2	433.04	6.32	6.29	15.01
578	15	T	2	50	F5	F2	495.44	6.60	7.02	11.23
579	15	T	3	75	F5	F1	464.07	8.32	7.78	17.38
580	15	T	2	60	F5	B	442.03	7.50	6.04	5.72
581	15	T	2	70	F8	F1	466.84	8.15	8.09	29.70
582	8	T	1	35	F5	F1	465.45	5.79	5.86	15.33
583	8	T	2	50	F5	F1	494.54	6.03	5.76	16.74
584	8	T	2	70	F4	B	496.36	8.23	8.09	16.41
585	19	T	1	25	F4	B	548.84	4.21	4.15	6.80
586	19	T	2	55	F4	B	573.40	4.82	5.12	11.23
587	19	T	3	90	F5	B	417.18	6.95	7.22	9.18
588	19	T	2	50	F5	F1	430.49	5.67	5.84	21.38
589	19	T	2	55	F5	F2	426.16	6.69	6.84	18.90
590	19	T	2	50	F5	B	439.77	6.12	5.70	9.39
591	12	T	1	30	F5	F2	399.80	5.40	11.78	6.80
592	12	T	2	50	F5	F1	398.11	5.67	7.57	10.37

593	12	T	2	50	F4	B	398.01	7.33	12.13	13.71
594	37	T	2	60	F5	F1	529.04	5.43	5.82	21.92
595	37	T	3	95	F8	F1	484.52	8.36	8.69	26.56
596	37	T	1	10	F4	B	591.09	4.21	4.45	8.53
597	37	T	1	40	F5	B	483.63	4.92	5.23	9.18
598	37	T	2	70	F5	F1	458.08	7.91	8.34	23.97
599	37	T	3	70	F5	F2	473.82	9.34	7.62	13.39
600	25	T	1	20	F5	B	442.44	6.50	5.60	7.02
601	25	T	2	60	F5	F1	450.35	7.98	7.35	19.54
602	25	T	3	80	F8	B	446.44	8.49	7.83	9.55
603	25	T	2	60	F5	B	426.33	7.83	6.41	11.23
604	25	T	2	55	F5	F2	449.55	8.02	8.34	12.53
605	47	T	1	30	F5	B	472.84	5.21	5.00	10.58
606	47	T	2	60	F5	B	438.45	7.01	6.67	12.31
607	47	T	3	95	F5	F1	496.19	8.54	8.39	18.68
608	47	T	2	50	F5	B	510.68	6.74	6.22	8.75
609	47	T	2	50	F5	B	561.94	7.16	5.87	11.12
610	47	T	3	80	F5	F2	511.80	7.91	7.50	17.60
611	47	T	2	50	F5	B	484.83	7.07	6.78	10.69
612	7	T	1	20	F5	F1	473.46	5.26	5.35	13.17
613	7	T	2	50	F8	F1	463.75	7.47	7.65	14.69
614	7	T	2	70	F5	F1	458.02	6.66	6.67	17.28
615	7	T	3	85	F4	F2	529.83	9.23	8.66	17.82
616	39	T	2	65	F5	F1	479.38	7.50	7.41	19.54
617	39	T	1	30	F5	B	453.33	6.01	5.43	10.37
618	39	T	3	80	F5	F1	426.29	7.36	6.84	20.52
619	39	T	2	70	F8	F1	438.44	7.94	7.77	22.46
620	10	T	2	40	F5	B	545.47	5.33	5.19	11.12
621	10	T	2	55	F5	B	465.49	6.01	6.06	6.80
622	10	T	3	70	F5	F2	522.53	6.66	6.32	6.37
623	10	T	1	30	F4	B	483.41	6.06	2.88	3.35
624	10	T	2	65	F4	B	495.32	7.07	4.11	7.88
625	3	T	1	40	F4	B	559.82	5.31	4.57	7.77
626	3	T	2	65	F5	B	594.47	7.91	6.64	7.88
627	3	T	1	30	F5	B	588.99	6.44	6.29	10.37
628	3	T	2	60	F5	B	503.45	8.18	6.99	5.94
629	3	T	2	55	F5	F2	453.81	8.23	7.62	12.20
630	3	T	2	50	F5	B	585.97	8.58	7.29	9.83
631	18	T	1	25	F5	B	428.00	5.06	4.48	10.58
632	18	T	2	55	F5	F1	444.59	7.83	7.66	16.30
633	18	T	1	35	F4	B	449.13	4.43	4.05	9.83
634	18	T	2	50	F5	F1	396.58	5.71	5.53	19.54
635	18	T	3	80	F8	F1	455.26	8.27	8.17	18.68
636	18	T	2	50	F5	F2	486.57	7.98	6.19	11.34
637	18	T	3	90	F5	F1	454.47	6.58	6.62	20.19
638	16	T	1	0	F4	B	573.73	4.34	4.38	9.83
639	16	T	2	60	F5	B	654.29	5.86	4.89	11.77
640	16	T	2	45	F5	F2	515.76	5.19	4.58	14.47
641	36	T	2	65	F5	F1	412.14	5.92	6.33	16.20
642	36	T	3	70	F8	F1	435.75	8.18	8.09	20.19

643	36	T	3	80	F5	F1	422.10	7.87	8.71	14.04
644	36	T	1	35	F5	F2	463.92	4.73	4.35	11.23
645	36	T	2	55	F5	F1	399.91	5.59	5.78	18.68
646	36	T	2	70	F5	F2	417.69	7.29	7.12	13.07
647	36	T	2	65	F5	F1	428.50	7.53	7.89	16.20
648	38	T	1	25	F5	B	480.03	5.03	2.97	12.96
649	38	T	1	40	F5	F2	448.72	5.38	5.45	14.25
650	38	T	2	45	F5	F1	519.74	6.08	5.40	20.19
651	38	T	2	60	F5	F1	499.51	7.94	7.45	23.65
652	9	T	2	45	F4	B	470.81	5.33	5.19	7.45
653	9	T	1	20	F5	B	480.51	4.73	4.52	8.85
654	35	T	1	20	F5	F1	412.53	5.30	5.20	17.82
655	35	T	2	60	F5	F1	427.32	7.91	7.56	16.74
656	35	T	1	20	F5	F1	466.24	5.82	6.44	15.98
657	35	T	2	70	F5	F1	460.50	8.07	7.41	30.99
658	35	T	3	90	F5	F1	437.20	8.36	7.66	21.92
659	35	T	3	85	F5	F1	440.19	8.11	8.09	20.84
660	48	T	1	30	F5	F2	493.96	5.46	5.60	12.31
661	48	T	3	70	F8	F1	487.16	8.36	7.93	16.95
662	48	T	2	45	F5	F1	517.05	6.40	6.38	19.87
663	48	T	3	110	F8	F1	503.48	9.17	9.31	22.46
664	48	T	3	60	F5	F1	483.05	8.49	7.60	15.55
665	34	T	1	20	F5	B	408.34	4.91	6.10	8.96
666	34	T	2	70	F5	F1	429.73	7.50	7.35	17.49
667	34	T	2	60	F5	F1	397.53	6.72	6.62	13.71
668	34	T	1	40	F5	F1	408.35	5.84	5.32	18.03
669	30	T	2	50	F5	F1	389.88	6.72	6.35	15.87
670	30	T	1	30	F4	B	397.62	4.17	4.07	12.20
671	30	T	1	25	F5	F1	406.44	5.71	5.62	21.38
672	30	T	2	60	F5	F1	429.85	8.18	8.17	18.25
673	28	T	2	50	F5	F1	473.22	6.60	6.87	16.74
674	28	T	1	20	F5	B	439.53	3.26	9.05	7.02
675	28	T	1	40	F4	B	424.93	4.33	7.46	7.23
676	28	T	2	50	F4	B	521.02	6.08	7.97	7.56
677	46	T	2	45	F5	F1	413.60	6.29	5.56	17.06
678	46	T	1	30	F5	F2	431.30	4.94	5.27	13.50
679	46	T	2	60	F5	F1	427.30	6.50	6.19	24.94
680	11	B	2	50	F5	F1	441.45	5.84	5.78	16.63
681	11	B	3	110	F5	F2	477.64	9.85	9.03	36.28
682	11	B	1	40	F8	F1	447.59	5.02	4.22	13.82
683	11	B	2	45	F5	F2	560.28	6.29	4.81	14.15
684	11	B	2	70	F5	F2	532.32	9.85	9.53	16.09
685	11	B	3	100	F8	F1	502.73	10.63	9.88	26.67
686	11	B	2	60	F5	F2	484.29	7.68	9.31	18.03
687	11	B	3	70	F5	F1	500.35	7.61	5.72	27.75
688	11	B	3	110	F11	F1	504.97	9.44	9.30	21.92
689	43	B	2	55	F5	F2	457.11	5.63	5.35	16.09
690	43	B	3	80	F5	F1	518.41	9.23	9.37	17.38
691	43	B	1	30	F4	B	469.75	4.25	4.74	13.07
692	43	B	1	40	F5	B	487.89	4.85	5.19	12.85

693	43	B	2	70	F5	F1	531.03	7.50	8.17	22.24
694	43	B	3	90	F8	F1	532.87	9.44	9.95	26.13
695	43	B	3	100	F8	F1	500.37	9.56	9.00	22.35
696	43	B	2	70	F5	B	512.98	6.25	9.15	12.53
697	18	B	1	35	F4	F2	443.99	3.54	3.49	15.55
698	18	B	1	40	F4	B	541.71	3.68	3.92	11.34
699	18	B	3	85	F4	B	481.18	4.39	4.82	11.01
700	18	B	4	85	F5	B	526.39	7.10	5.63	25.00
701	18	B	2	15	F4	F2	459.86	4.03	3.90	13.71
702	18	B	4	120	F5	F1	462.56	7.27	7.12	34.34
703	18	B	2	35	F4	F1	489.36	4.01	4.06	12.63
704	18	B	2	60	F5	F2	459.83	8.11	8.26	14.69
705	18	B	2	50	F5	F2	479.59	6.60	6.79	20.41
706	18	B	2	65	F5	F1	478.65	6.37	6.56	22.78
707	18	B	3	70	F8	F1	503.77	8.58	8.52	31.10
708	18	B	3	80	F8	F1	502.01	7.64	6.75	41.68
709	18	B	3	90	F5	F1	482.26	6.69	6.30	31.31
710	18	B	3	85	F5	F1	567.54	6.69	8.85	24.83
711	44	B	1	30	F4	B	512.31	4.41	4.26	14.04
712	44	B	2	60	F5	B	493.80	6.80	6.44	14.15
713	44	B	1	25	F4	B	480.57	3.64	3.89	11.34
714	44	B	1	40	F5	F1	464.22	4.94	4.82	19.98
715	44	B	2	65	F5	F1	488.87	6.37	6.87	28.72
716	44	B	2	60	F5	F1	502.60	6.50	6.16	22.24
717	44	B	3	80	F5	B	527.81	7.79	7.52	12.74
718	44	B	2	70	F5	F2	495.99	7.64	6.51	23.65
719	44	B	2	65	F5	F1	524.06	6.03	6.41	32.72
720	44	B	3	80	F8	F1	528.60	8.27	8.55	38.12
721	44	B	4	120	F8	F1	521.32	9.50	10.02	53.88
722	47	B	1	10	F4	B	475.37	4.69	4.46	7.77
723	47	B	2	50	F5	F2	511.37	6.60	6.75	17.28
724	47	B	4	100	F8	F1	530.37	10.16	9.53	32.18
725	47	B	2	60	F5	B	505.23	6.32	6.19	13.71
726	47	B	3	100	F8	F1	529.67	9.85	7.66	21.92
727	47	B	4	100	F8	F1	545.84	11.90	10.77	18.25
728	47	B	2	60	F5	B	544.65	8.82	8.47	15.23
729	47	B	2	60	F5	B	537.31	8.23	6.02	9.61
730	47	B	4	100	F11	F1	529.18	10.29	9.87	31.85
731	47	B	3	110	F8	B	551.86	9.44	8.85	16.09
732	47	B	4	100	F8	F1	507.14	9.50	10.69	19.33
733	47	B	3	100	F5	B	519.84	7.23	11.78	10.04
734	3	B	1	30	F4	B	521.98	4.36	4.10	9.39
735	3	B	2	50	F5	F2	596.11	6.47	6.41	16.84
736	3	B	3	120	F8	F1	527.64	10.29	9.40	30.45
737	3	B	2	50	F4	B	516.48	4.88	4.93	14.25
738	3	B	3	130	F11	F1	531.91	12.36	12.21	56.80
739	3	B	3	110	F8	F1	531.16	10.43	10.40	37.58
740	3	B	2	70	F5	F1	547.71	7.53	7.66	21.38
741	3	B	3	130	F11	F1	543.89	10.99	11.45	31.64
742	3	B	3	85	F8	F1	533.76	9.78	9.40	23.86

743	3	B	3	80	F5	F2	511.78	8.92	8.60	13.82
744	31	T	1	30	F5	F2	431.92	5.55	5.67	14.36
745	31	T	2	60	F5	B	425.17	5.50	5.23	13.17
746	31	T	2	50	F5	F1	452.01	6.50	7.22	23.86
747	31	T	2	60	F5	F1	488.18	7.50	7.35	20.95
748	31	T	3	75	F8	F1	454.37	9.50	9.77	32.29
749	41	B	2	65	F8	F1	453.66	8.54	7.66	17.92
750	41	B	2	60	F5	F1	470.38	8.45	7.63	19.87
751	41	B	1	35	F5	F2	466.34	6.34	6.50	15.87
752	41	B	3	100	F8	F1	524.23	10.29	9.94	23.32
753	41	B	3	90	F8	F1	535.75	9.85	9.31	23.32
754	41	B	2	70	F8	F1	512.60	8.58	9.60	21.70
755	41	B	3	120	F11	F1	542.74	12.43	11.00	33.80
756	41	B	3	120	F8	F1	560.24	10.43	10.40	27.10
757	19	B	1	40	F4	F2	517.71	3.54	3.36	15.44
758	19	B	1	40	F4	B	502.62	3.58	3.72	11.12
759	19	B	2	45	F5	F2	449.92	4.88	4.48	10.69
760	19	B	2	20	F4	F2	530.58	3.84	3.97	11.34
761	19	B	3	80	F5	F1	493.85	5.48	5.56	25.59
762	19	B	2	40	F5	F1	475.38	4.71	4.71	21.38
763	19	B	2	50	F5	B	479.44	4.45	4.26	11.23
764	19	B	3	80	F5	F2	444.03	6.12	6.44	14.25
765	19	B	3	70	F5	F2	477.75	7.40	7.56	14.58
766	19	B	3	85	F5	F1	480.01	7.16	6.26	17.38
767	19	B	3	60	F5	F2	496.52	6.03	5.70	13.50
768	7	B	1	35	F8	F1	571.68	4.18	4.36	14.04
769	7	B	1	45	F4	F2	488.57	4.72	4.87	17.71
770	7	B	2	50	F5	F1	507.01	5.55	5.93	32.93
771	7	B	2	55	F8	F1	562.40	9.23	8.71	22.78
772	7	B	2	65	F5	F1	514.73	8.87	8.94	22.57
773	7	B	2	70	F5	B	515.73	7.79	8.52	18.57
774	29	B	1	0	F4	B	533.67	4.65	4.58	11.12
775	29	B	1	40	F4	F2	559.65	4.36	4.45	16.84
776	29	B	2	70	F5	F1	542.17	6.63	7.05	29.37
777	29	B	2	60	F5	B	549.51	7.83	7.60	14.58
778	29	B	2	65	F8	F1	564.66	8.82	9.09	31.53
779	29	B	3	60	F5	F2	545.08	7.29	7.22	17.71
780	21	B	2	45	F5	F1	419.57	6.10	5.72	26.24
781	21	B	1	30	F5	F2	464.69	4.53	4.48	15.66
782	21	B	2	50	F5	F1	464.41	5.61	5.50	23.00
783	21	B	3	120	F8	F1	510.66	10.36	11.03	44.81
784	21	B	3	90	F8	F1	448.97	8.77	8.88	36.71
785	21	B	2	70	F8	F1	489.17	9.67	9.79	19.33
786	24	B	1	20	F5	F2	501.08	5.53	5.53	17.06
787	24	B	2	65	F5	F1	546.01	6.47	6.71	20.63
788	24	B	3	90	F11	F1	593.94	10.29	9.88	23.54
789	24	B	2	50	F8	F1	552.03	9.17	8.26	23.32
790	24	B	3	100	F11	F1	586.00	10.70	10.79	38.55
791	24	B	3	85	F11	F1	594.28	11.31	9.88	28.94
792	6	B	1	20	F4	F2	484.03	3.94	3.83	12.96

793	6	B	2	65	F5	F1	507.01	5.33	5.04	27.86
794	6	B	1	40	F4	F2	503.49	3.71	4.22	14.15
795	6	B	2	45	F4	F1	521.68	3.98	4.11	28.51
796	6	B	3	90	F5	F2	536.41	6.34	5.56	29.05
797	6	B	2	45	F5	F2	508.09	4.52	4.35	15.12
798	6	B	2	50	F5	F1	513.38	5.92	5.48	27.32
799	6	B	2	55	F5	F1	499.93	6.53	6.85	21.92
800	6	B	2	65	F5	F1	552.24	8.18	6.41	26.89
801	6	B	3	100	F5	F1	517.77	7.57	8.05	27.53
802	8	B	1	40	F5	F1	499.96	4.40	4.70	16.41
803	8	B	2	60	F5	F2	514.06	5.50	5.70	21.60
804	8	B	2	55	F8	F1	482.76	7.75	5.62	16.52
805	8	B	2	125	F5	F1	563.56	8.58	9.31	47.94
806	8	B	2	65	F8	F1	541.54	9.85	9.77	17.38
807	9	B	1	20	F5	F1	476.86	3.71	3.59	9.61
808	9	B	1	25	F4	B	432.38	4.27	4.38	13.39
809	9	B	2	70	F5	B	478.86	7.64	8.17	15.77
810	9	B	2	50	F5	B	460.77	5.25	5.20	25.27
811	9	B	3	100	F8	F2	510.26	10.29	9.43	23.76
812	9	B	2	70	F5	F2	455.94	7.87	6.90	9.50
813	9	B	3	80	F8	F1	461.50	7.71	8.05	20.52
814	48	B	1	10	F4	B	425.11	3.62	3.59	12.53
815	48	B	2	50	F5	F1	434.77	5.08	4.99	18.90
816	48	B	1	40	F4	B	470.78	3.71	3.54	5.94
817	48	B	2	20	F4	B	525.84	5.42	4.46	6.26
818	48	B	2	50	F5	B	440.35	6.10	5.78	8.21
819	48	B	2	70	F5	F1	429.63	7.75	9.06	27.21
820	34	B	1	40	F4	B	467.31	3.86	3.11	6.70
821	34	B	1	45	F5	F1	437.71	4.67	4.68	15.98
822	34	B	3	70	F5	F1	488.10	7.50	7.09	22.57
823	34	B	2	45	F5	B	474.80	5.63	5.18	14.36
824	34	B	4	120	F8	F1	526.90	10.09	10.13	42.11
825	34	B	2	65	F5	F1	453.18	6.95	6.41	22.57
826	34	B	2	70	F8	F2	488.24	8.45	6.95	14.36
827	14	B	2	45	F5	F1	471.40	6.47	4.77	20.52
828	14	B	1	30	F5	F2	462.09	5.53	5.08	13.28
829	14	B	3	85	F5	B	493.29	7.07	6.44	31.96
830	14	B	1	45	F5	F2	440.99	4.85	6.19	15.77
831	14	B	2	55	F4	F1	476.30	6.63	5.99	13.93
832	14	B	3	90	F5	F1	482.73	5.95	12.05	39.95
833	26	B	1	30	F4	B	423.38	4.53	4.41	11.12
834	26	B	2	60	F5	F1	441.57	7.36	7.05	19.33
835	26	B	1	30	F4	B	434.25	3.74	3.65	10.15
836	26	B	2	60	F5	F2	459.47	4.79	5.13	15.33
837	26	B	2	45	F5	F1	475.86	5.54	6.43	27.21
838	26	B	2	50	F5	F2	496.88	7.36	6.48	21.92
839	26	B	3	90	F5	F1	468.30	8.41	8.94	22.89
840	26	B	2	70	F5	B	432.55	6.69	6.41	11.01
841	26	B	2	60	F4	B	455.25	4.41	4.63	14.15
842	28	B	2	50	F5	B	469.72	7.04	7.57	8.85

843	28	B	2	70	F5	F1	550.16	6.42	6.59	19.54
844	28	B	3	80	F8	F1	547.45	10.04	9.77	30.34
845	28	B	1	40	F5	F1	525.39	5.88	5.78	23.22
846	28	B	3	70	F8	F1	585.92	8.07	7.62	32.29
847	28	B	2	70	F8	F1	561.74	8.97	9.00	25.48
848	28	B	2	50	F5	F1	528.85	7.47	7.66	17.60
849	28	B	3	100	F11	F1	566.75	10.04	10.02	38.33
850	45	B	1	30	F4	B	423.11	3.28	3.65	11.99
851	45	B	1	30	F4	B	451.40	3.88	3.89	15.77
852	45	B	2	70	F5	F2	415.99	5.90	6.19	14.90
853	45	B	4	130	F5	F1	487.08	8.23	12.21	31.10
854	45	B	3	75	F5	F1	395.91	8.97	7.35	17.06
855	45	B	1	45	F4	F1	403.40	4.40	4.48	20.63
856	45	B	2	65	F5	F1	450.08	6.63	6.75	20.30
857	45	B	2	50	F5	F1	433.11	5.05	5.45	21.70
858	45	B	2	60	F5	F2	472.74	5.97	6.13	13.61
859	45	B	2	45	F5	F1	427.17	5.05	5.04	13.93
860	45	B	3	70	F5	F1	480.35	7.91	7.52	29.80
861	45	B	2	60	F5	F1	525.75	6.92	6.96	21.92
862	45	B	3	90	F5	F1	462.20	7.27	7.88	36.82
863	45	B	3	80	F8	F1	493.12	7.94	7.26	14.69
864	16	B	2	50	F4	B	460.76	4.12	4.11	13.93
865	16	B	3	110	F5	F1	490.17	7.07	7.22	18.36
866	16	B	2	50	F5	B	492.68	5.23	4.82	9.61
867	16	B	2	50	F4	B	465.09	5.00	5.00	12.53
868	16	B	1	15	F4	B	484.45	3.66	3.67	10.69
869	16	B	2	30	F4	B	455.23	3.86	3.80	10.15
870	16	B	3	85	F5	F2	485.96	5.28	5.72	11.44
871	2	B	1	20	F4	B	501.12	2.93	3.20	11.01
872	2	B	2	45	F4	F1	474.00	3.50	3.64	18.14
873	2	B	1	30	F4	F2	478.81	3.62	3.36	15.98
874	2	B	2	40	F4	F2	440.59	3.57	3.83	14.36
875	2	B	2	45	F5	F1	466.42	5.63	5.70	24.08
876	2	B	2	40	F4	F1	426.47	5.55	4.91	17.38
877	2	B	3	120	F5	F1	493.19	6.44	6.48	32.18
878	12	B	1	35	F5	F1	435.53	3.78	4.18	11.01
879	12	B	2	45	F5	F1	423.83	4.39	3.99	20.95
880	12	B	3	75	F5	F2	438.55	7.27	7.39	13.07
881	12	B	1	30	F4	B	449.23	4.69	5.16	6.37
882	12	B	3	95	F5	F2	431.74	7.94	8.09	26.24
883	12	B	2	55	F4	F1	474.25	4.91	5.22	24.19
884	27	B	2	55	F5	F1	497.05	5.44	6.66	28.18
885	27	B	2	60	F8	F1	486.92	7.79	7.77	33.69
886	27	B	1	25	F5	F1	502.42	4.76	4.68	21.70
887	27	B	2	70	F5	F1	455.42	4.76	5.35	17.06
888	27	B	2	70	F5	F1	473.70	6.25	6.13	20.95
889	27	B	3	70	F8	F2	483.08	9.44	9.60	19.22
890	27	B	1	30	F5	F1	551.26	5.25	5.02	21.27
891	27	B	3	70	F8	F1	480.43	8.68	8.26	22.78
892	27	B	3	80	F8	F1	511.82	9.97	10.02	26.24

893	27	B	3	120	F8	F1	497.18	8.63	8.55	23.22
894	32	B	1	50	F5	F1	413.33	6.67	5.53	11.99
895	32	B	1	50	F5	B	419.38	4.53	5.13	9.83
896	32	B	2	40	F5	F1	451.60	5.16	6.48	16.95
897	32	B	3	100	F8	F1	458.88	7.64	8.60	24.62
898	32	B	2	45	F5	F1	432.80	6.22	6.94	19.43
899	32	B	2	80	F5	F1	475.55	6.63	7.93	17.82
900	32	B	3	75	F8	F1	469.82	9.02	9.70	31.53
901	23	B	1	30	F5	F2	461.92	4.73	4.64	15.23
902	23	B	2	60	F5	F2	456.69	7.48	6.67	11.44
903	23	B	1	30	F4	F2	461.75	4.50	5.94	14.90
904	23	B	2	70	F5	F1	464.19	6.98	9.70	35.74
905	23	B	2	70	F8	F1	544.94	7.98	8.52	32.50
906	23	B	2	70	F5	B	469.00	7.91	8.76	10.47
907	1	B	1	20	F4	B	456.36	3.55	3.22	9.72
908	1	B	2	20	F4	B	446.36	3.84	3.64	16.20
909	1	B	3	90	F5	F1	485.27	6.29	7.05	31.10
910	1	B	2	45	F5	F2	422.88	4.47	4.44	16.52
911	1	B	3	70	F8	F1	482.84	10.22	10.32	31.96
912	1	B	2	70	F5	F1	437.66	6.12	5.50	19.43
913	1	B	2	60	F5	F1	523.74	7.43	7.12	21.60
914	2	T	1	40	F4	F1	458.24	3.51	4.03	8.64
915	2	T	2	35	F5	F2	413.30	4.36	4.85	16.41

B = butt log; M = middle log; T = top log

APPENDIX 1B: RESULTS OF COMPRESSION STRENGTH PARALLEL TO THE GRAIN FOR THE FIVE LOW, FIVE MEDIUM AND FIVE HIGH STIFFNESS TREES

Tree No.	Group based on stiffness	Log Type	Position from Pith	Machine Stress Grade	Visual Grade	Distance from Pith (mm)	MOE (GPa) (Tension)	M.C (%)	Density (kg/cu.m)	MCS (MPa)
11	G3	T	2	F4	B	40	7.09	12.50	416.65	27.37
11	G3	T	2	F5	F1	40	5.07	11.00	430.39	33.27
11	G3	T	1	F5	F1	30	6.30	12.00	464.01	22.06
11	G3	T	3	F8	F1	115	7.12	10.50	528.49	21.37
11	G3	T	2	F5	F1	55	6.79	11.50	435.96	25.90
24	G3	T	2	F8	F1	55	8.80	12.00	454.98	30.92
24	G3	T	1	F5	F2	25	5.82	12.00	447.73	24.54
24	G3	T	2	F5	F2	60	8.09	12.00	507.44	22.32
24	G3	T	3	F8	F1	90	10.92	11.50	456.31	33.08
24	G3	T	3	F5	B	90	8.26	12.00	492.34	23.81
24	G3	T	2	F8	F1	55	9.15	12.50	510.87	31.68
41	G3	M	1	F5	B	30	5.56	12.50	454.66	38.16
41	G3	M	1	F4	B	30	6.56	12.00	417.36	20.25
41	G3	M	3	F5	B	80	9.16	11.50	499.60	25.08
41	G3	M	2	F5	F1	65	8.09	11.00	485.42	22.73
41	G3	M	2	F5	F1	70	8.60	10.50	483.63	28.06
9	G2	M	1	F5	F2	30	4.63	11.00	559.81	23.81
9	G2	M	1	F5	F2	25	6.09	11.50	558.80	22.67
9	G2	M	2	F5	F1	40	5.30	12.00	400.24	30.92
9	G2	M	2	F4	B	55	7.31	11.50	429.98	17.84
28	G3	M	1	F4	F1	25	5.26	10.50	437.92	20.54
28	G3	M	2	F5	F1	60	7.18	12.00	483.32	29.08
28	G3	M	3	F8	F1	115	10.13	11.50	532.45	31.87
28	G3	M	1	F5	F1	30	5.62	11.50	428.19	20.06
28	G3	M	3	F5	F2	80	8.52	11.50	506.54	20.92
28	G3	M	3	F5	F1	100	9.37	12.00	482.73	22.70
28	G3	M	2	F8	F1	50	9.60	11.50	498.65	33.17
25	G1	M	1	F5	B	30	5.54	11.00	419.00	17.78
25	G1	M	2	F5	F2	60	6.51	11.00	412.63	39.68
25	G1	M	2	F8	F1	65	7.22	12.00	414.15	27.65
25	G1	M	3	F8	F2	100	8.27	11.50	467.44	25.49
25	G1	M	2	F8	F1	70	7.96	11.00	444.85	32.16
25	G1	M	2	F8	F2	65	8.04	11.00	438.20	26.98
16	G1	M	1	F5	F1	10	4.54	12.50	514.23	22.06
16	G1	M	2	F4	B	45	4.63	12.00	421.54	19.27
16	G1	M	3	F4	B	70	5.60	12.00	520.29	23.81
16	G1	M	2	F5	F2	55	5.11	11.00	421.21	22.60
16	G1	M	3	F5	F2	65	9.31	11.50	449.51	18.70
16	G1	M	2	F5	B	60	6.03	11.00	470.77	36.16
5	G1	M	1	F5	F2	30	4.68	11.00	469.27	26.57
5	G1	M	2	F5	F1	55	5.51	12.50	494.03	25.81
5	G1	M	3	F5	F1	65	7.12	11.50	486.94	16.51
5	G1	M	3	F8	F1	110	9.95	11.00	550.78	37.49
5	G1	M	1	F5	F2	30	4.82	12.50	437.22	23.81
5	G1	M	2	F5	F1	55	6.12	11.50	448.38	21.24
5	G1	M	2	F5	F1	70	7.66	11.50	496.15	23.68

5	G1	M	2	F5	F2	55	6.72	12.50	480.69	26.06
5	G1	M	2	F5	F1	70	7.09	11.50	465.51	15.49
5	G1	M	2	F5	F1	70	11.95	11.50	532.19	24.92
5	G1	M	3	F8	F1	105	8.05	12.00	496.07	22.22
36	G2	M	1	F4	B	40	5.98	10.50	466.24	22.41
36	G2	M	2	F5	B	60	7.10	12.50	477.82	28.35
36	G2	M	3	F8	F2	95	7.98	11.00	431.67	34.60
36	G2	M	2	F5	F2	50	5.51	11.50	442.81	27.94
36	G2	M	3	F8	F1	70	8.52	11.00	439.55	31.94
36	G2	M	3	F5	F2	70	8.34	10.50	429.64	24.41
36	G2	M	2	F8	F1	70	8.22	11.00	476.58	30.29
11	G3	M	1	F5	F2	30	5.10	12.00	436.34	18.57
11	G3	M	2	F8	F1	60	7.29	11.00	433.60	28.57
11	G3	M	2	F5	F1	70	8.71	12.00	458.76	28.00
11	G3	M	2	F5	F1	55	5.56	12.50	440.21	24.32
11	G3	M	3	F5	F1	85	9.53	11.00	462.47	27.46
11	G3	M	3	F5	F2	115	16.34	12.00	425.71	20.73
18	G1	M	1	F4	B	40	4.74	11.00	422.08	20.54
18	G1	M	1	F5	B	40	4.35	12.00	432.01	30.35
18	G1	M	3	F5	F1	70	8.52	11.00	454.23	24.22
18	G1	M	2	F5	B	70	5.19	12.00	425.82	29.21
18	G1	M	3	F5	F1	100	7.18	10.50	451.64	25.71
18	G1	M	2	F5	F1	70	7.35	11.00	451.73	26.98
18	G1	M	4	F8	F1	110	8.39	12.50	434.91	27.30
18	G1	M	2	F5	F1	55	6.13	11.50	424.51	31.75
18	G1	M	3	F5	B	85	6.02	12.00	499.84	26.70
29	G2	M	1	F4	B	10	3.79	10.50	417.62	18.92
29	G2	M	2	F5	F2	50	6.96	11.50	449.40	25.33
29	G2	M	3	F5	F1	80	8.17	11.00	466.89	19.46
29	G2	M	2	F5	F1	50	6.51	12.50	484.38	35.24
29	G2	M	3	F8	F1	90	10.92	11.50	533.17	41.43
24	G3	M	1	F5	B	30	6.33	11.50	468.32	25.94
24	G3	M	2	F5	F1	60	8.17	12.00	510.12	25.71
24	G3	M	3	F8	F1	50	8.85	11.50	520.80	31.43
24	G3	M	3	F8	F1	70	10.21	11.00	597.69	30.16
24	G3	M	2	F8	F2	95	8.71	11.50	465.11	34.92
17	G2	M	2	F5	F1	40	6.33	11.50	421.59	20.63
17	G2	M	1	F4	B	10	4.13	10.50	451.30	27.94
17	G2	M	2	F5	F2	60	5.36	11.50	402.12	23.90
17	G2	M	2	F8	F2	70	7.52	12.00	472.86	23.30
17	G2	M	2	F5	F1	70	7.98	11.00	453.30	23.97
7	G2	M	2	F5	F1	50	6.41	12.00	482.93	20.63
7	G2	M	2	F5	F2	65	8.47	11.50	529.93	28.22
7	G2	M	1	F8	F1	30	5.97	11.00	455.31	38.73
7	G2	M	2	F5	F2	70	7.31	11.50	463.87	20.98
2	G1	M	1	F5	F1	20	3.22	11.00	449.67	24.19
2	G1	M	2	F4	B	40	4.11	12.00	435.61	21.14
2	G1	M	2	F4	F1	45	4.34	12.50	408.26	21.46
3	G3	M	1	F8	F2	20	5.47	11.00	486.64	30.48
3	G3	M	2	F5	F1	60	9.32	10.50	518.98	22.98
3	G3	M	3	F11	F1	130	11.95	11.00	530.23	34.60
3	G3	M	1	F5	F2	30	4.68	11.00	466.80	26.35

3	G3	M	2	F5	F2	60	6.91	11.50	473.51	34.38
3	G3	M	2	F5	F1	65	9.00	11.50	494.74	20.63
3	G3	M	2	F8	F2	70	8.60	11.50	484.93	25.14
36	G2	B	1	F4	B	25	4.51	12.50	474.70	17.46
36	G2	B	2	F5	F1	60	6.79	11.00	437.86	34.92
36	G2	B	1	F4	F1	40	4.08	12.00	499.37	26.22
36	G2	B	2	F5	F1	60	6.23	11.50	425.65	20.70
36	G2	B	3	F8	F1	100	8.85	11.00	488.03	29.52
36	G2	B	2	F8	F1	110	7.41	11.00	476.50	40.95
36	G2	B	2	F5	F2	70	7.12	12.50	430.02	20.32
36	G2	B	2	F5	F1	60	6.96	12.00	449.16	18.10
17	G2	B	1	F5	B	30	4.58	11.50	470.89	18.16
17	G2	B	3	F5	F1	70	6.26	11.00	464.50	20.95
17	G2	B	2	F5	F1	55	5.18	11.50	492.11	20.73
17	G2	B	3	F5	F1	70	7.77	12.00	486.51	27.30
17	G2	B	3	F5	F1	85	8.05	11.00	450.74	24.44
17	G2	B	2	F5	F1	70	7.56	11.00	467.56	33.37
5	G1	B	1	F4	B	15	3.40	11.50	493.48	17.46
5	G1	B	2	F4	F2	45	4.10	12.00	427.19	20.83
5	G1	B	3	F5	F1	90	5.64	11.50	500.16	24.57
5	G1	B	2	F4	F2	25	3.82	12.00	523.26	17.78
5	G1	B	2	F5	F1	65	4.69	11.50	649.78	26.67
5	G1	B	4	F5	F1	90	9.96	12.50	565.28	34.22
5	G1	B	3	F5	F1	70	7.41	11.50	507.47	25.59
5	G1	B	3	F5	F1	90	6.12	11.50	548.44	22.86
5	G1	B	3	F5	F1	85	5.75	11.00	495.47	21.17
5	G1	B	2	F5	F2	45	5.90	12.00	490.25	22.32
5	G1	B	3	F5	F1	70	6.75	12.50	517.52	15.87
5	G1	B	4	F8	F1	120	8.09	11.50	542.06	25.90
5	G1	B	2	F4	F1	30	4.07	11.50	568.11	18.19
25	G1	B	2	F5	F1	40	6.59	12.00	418.31	24.51
25	G1	B	2	F8	F1	70	7.57	11.50	514.74	27.94
25	G1	B	1	F5	B	40	5.79	12.50	459.80	27.40
25	G1	B	2	F5	B	50	6.36	12.00	464.26	23.81
25	G1	B	3	F8	F1	100	8.60	12.00	530.88	24.54
25	G1	B	2	F5	B	60	9.32	12.00	440.89	25.90
25	G1	B	4	F11	F1	100	9.77	11.00	468.82	34.29
25	G1	B	3	F8	F1	110	9.00	12.00	547.55	23.30
25	G1	B	4	F8	F1	95	9.15	12.00	517.22	36.51
5	G1	T	1	F5	F2	30	5.09	12.00	477.81	20.03
5	G1	T	1	F5	F1	30	4.97	12.00	531.37	22.86
5	G1	T	2	F5	B	60	6.26	11.50	521.79	20.22
5	G1	T	2	F5	F1	50	5.93	12.00	491.60	25.21
5	G1	T	2	F5	F1	60	8.05	12.00	472.71	25.62
5	G1	T	2	F5	F1	65	7.22	12.00	499.93	19.49
5	G1	T	3	F8	F1	70	6.71	11.00	495.27	31.87
5	G1	T	3	F8	F1	90	8.09	12.00	503.24	41.33
17	G2	T	1	F4	B	10	4.34	11.00	529.58	27.49
17	G2	T	2	F5	F2	45	6.03	11.50	430.79	22.67
17	G2	T	2	F5	F1	40	6.22	11.50	407.28	27.94
17	G2	T	3	F8	F1	80	7.98	11.50	449.69	31.14
41	G3	T	1	F5	B	40	4.98	12.50	449.66	25.46

41	G3	T	2	F5	F1	50	5.78	12.00	461.33	28.35
41	G3	T	3	F8	F2	90	8.09	11.50	489.26	30.57
41	G3	T	2	F5	F2	50	7.22	11.00	479.42	27.94
41	G3	T	2	F5	B	50	7.32	12.50	460.30	28.03
29	G2	T	2	F5	B	50	6.64	12.00	512.20	26.67
29	G2	T	2	F8	F1	60	7.98	10.50	501.61	30.32
29	G2	T	2	F5	F1	60	7.36	12.50	465.56	28.32
29	G2	T	1	F5	F2	30	6.99	12.00	449.61	23.46
25	G1	T	1	F5	B	20	5.60	11.00	442.44	24.00
25	G1	T	2	F5	F1	60	7.35	11.50	450.35	34.92
25	G1	T	3	F8	B	80	7.83	10.50	446.44	25.56
25	G1	T	2	F5	B	60	6.41	12.50	426.33	18.57
25	G1	T	2	F5	F2	55	8.34	12.50	449.55	22.79
7	G2	T	1	F5	F1	20	5.35	12.50	473.46	28.73
7	G2	T	2	F8	F1	50	7.65	12.00	463.75	32.51
7	G2	T	2	F5	F1	70	6.67	10.50	458.02	22.29
7	G2	T	3	F4	F2	85	8.66	12.00	529.83	14.92
3	G3	T	1	F4	B	40	4.57	11.00	559.82	20.63
3	G3	T	2	F5	B	65	6.64	12.00	594.47	22.86
3	G3	T	1	F5	B	30	6.29	11.50	588.99	32.16
3	G3	T	2	F5	B	60	6.99	11.00	503.45	22.86
3	G3	T	2	F5	F2	55	7.62	11.00	453.81	24.13
3	G3	T	2	F5	B	50	7.29	12.00	585.97	25.27
18	G1	T	1	F5	B	25	4.48	11.50	428.00	26.67
18	G1	T	2	F5	F1	55	7.66	12.50	444.59	35.56
18	G1	T	1	F4	B	35	4.05	12.50	449.13	26.51
18	G1	T	2	F5	F1	50	5.53	12.00	396.58	24.32
18	G1	T	3	F8	F1	80	8.17	10.50	455.26	43.33
18	G1	T	2	F5	F2	50	6.19	11.50	486.57	24.10
18	G1	T	3	F5	F1	90	6.62	12.50	454.47	20.00
16	G1	T	1	F4	B	0	4.38	12.00	573.73	22.83
16	G1	T	2	F5	B	60	4.89	11.00	654.29	22.03
16	G1	T	2	F5	F2	45	4.58	12.00	515.76	29.84
36	G2	T	2	F5	F1	65	6.33	12.50	412.14	22.60
36	G2	T	3	F8	F1	70	8.09	11.00	435.75	30.00
36	G2	T	3	F5	F1	80	8.71	11.50	422.10	25.71
36	G2	T	1	F5	F2	35	4.35	12.00	463.92	36.51
36	G2	T	2	F5	F1	55	5.78	11.50	399.91	37.43
36	G2	T	2	F5	F2	70	7.12	11.00	417.69	31.43
36	G2	T	2	F5	F1	65	7.89	11.00	428.50	24.10
9	G2	T	2	F4	B	45	5.19	11.50	470.81	31.11
9	G2	T	1	F5	B	20	4.52	12.50	480.51	25.17
28	G3	T	2	F5	F1	50	6.87	12.50	473.22	26.98
28	G3	T	1	F5	B	20	9.05	11.00	439.53	27.02
28	G3	T	1	F4	B	40	7.46	11.50	424.93	22.48
28	G3	T	2	F4	B	50	7.97	10.50	521.02	19.24
11	G3	B	2	F5	F1	50	5.78	12.00	441.45	19.46
11	G3	B	3	F5	F2	110	9.03	12.00	477.64	18.79
11	G3	B	1	F8	F1	40	4.22	12.00	447.59	28.63
11	G3	B	2	F5	F2	45	4.81	11.00	560.28	22.00
11	G3	B	2	F5	F2	70	9.53	11.00	532.32	21.11
11	G3	B	3	F8	F1	100	9.88	11.00	502.73	34.70

11	G3	B	2	F5	F2	60	9.31	11.50	484.29	32.83
11	G3	B	3	F5	F1	70	5.72	11.00	500.35	26.03
11	G3	B	3	F11	F1	110	9.30	12.00	504.97	31.11
18	G1	B	1	F4	F2	35	3.49	12.00	443.99	16.83
18	G1	B	1	F4	B	40	3.92	11.50	541.71	22.22
18	G1	B	3	F4	B	85	4.82	12.00	481.18	32.38
18	G1	B	4	F5	B	85	5.63	11.00	526.39	29.81
18	G1	B	2	F4	F2	15	3.90	12.00	459.86	21.40
18	G1	B	4	F5	F1	120	7.12	12.50	462.56	27.08
18	G1	B	2	F4	F1	35	4.06	11.50	489.36	23.84
18	G1	B	2	F5	F2	60	8.26	12.00	459.83	26.03
18	G1	B	2	F5	F2	50	6.79	11.00	479.59	21.59
18	G1	B	2	F5	F1	65	6.56	12.00	478.65	28.95
18	G1	B	3	F8	F1	70	8.52	11.00	503.77	30.79
18	G1	B	3	F8	F1	80	6.75	10.50	502.01	28.10
18	G1	B	3	F5	F1	90	6.30	12.50	482.26	20.03
18	G1	B	3	F5	F1	85	8.85	12.00	567.54	23.33
3	G3	B	1	F4	B	30	4.10	12.50	521.98	28.73
3	G3	B	2	F5	F2	50	6.41	12.50	596.11	19.11
3	G3	B	3	F8	F1	120	9.40	11.50	527.64	29.65
3	G3	B	2	F4	B	50	4.93	12.00	516.48	21.27
3	G3	B	3	F11	F1	130	12.21	12.00	531.91	40.83
3	G3	B	3	F8	F1	110	10.40	11.00	531.16	39.43
3	G3	B	2	F5	F1	70	7.66	11.00	547.71	23.17
3	G3	B	3	F11	F1	130	11.45	11.00	543.89	32.63
3	G3	B	3	F8	F1	85	9.40	10.50	533.76	34.63
3	G3	B	3	F5	F2	80	8.60	11.50	511.78	21.65
41	G3	B	2	F8	F1	65	7.66	11.50	453.66	30.29
41	G3	B	2	F5	F1	60	7.63	12.00	470.38	27.94
41	G3	B	1	F5	F2	35	6.50	12.50	466.34	23.17
41	G3	B	3	F8	F1	100	9.94	11.00	524.23	27.94
41	G3	B	3	F8	F1	90	9.31	11.00	535.75	36.19
41	G3	B	2	F8	F1	70	9.60	11.00	512.60	28.70
41	G3	B	3	F11	F1	120	11.00	11.50	542.74	39.08
41	G3	B	3	F8	F1	120	10.40	11.50	560.24	35.97
7	G2	B	1	F8	F1	35	4.36	10.50	571.68	26.00
7	G2	B	1	F4	F2	45	4.87	12.00	488.57	21.90
7	G2	B	2	F5	F1	50	5.93	11.00	507.01	19.78
7	G2	B	2	F8	F1	55	8.71	11.50	562.40	26.51
7	G2	B	2	F5	F1	65	8.94	12.50	514.73	24.67
7	G2	B	2	F5	B	70	8.52	12.00	515.73	18.10
29	G2	B	1	F4	B	0	4.58	10.50	533.67	21.59
29	G2	B	1	F4	F2	40	4.45	12.00	559.65	25.24
29	G2	B	2	F5	F1	70	7.05	11.00	542.17	21.59
29	G2	B	2	F5	B	60	7.60	12.00	549.51	24.13
29	G2	B	2	F8	F1	65	9.09	12.00	564.66	29.52
29	G2	B	3	F5	F2	60	7.22	11.50	545.08	23.81
24	G3	B	1	F5	F2	20	5.53	11.50	501.08	22.73
24	G3	B	2	F5	F1	65	6.71	11.00	546.01	30.79
24	G3	B	3	F11	F1	90	9.88	11.00	593.94	30.48
24	G3	B	2	F8	F1	50	8.26	11.00	552.03	43.84
24	G3	B	3	F11	F1	100	10.79	11.50	586.00	34.29

24	G3	B	3	F11	F1	85	9.88	11.50	594.28	33.33
9	G2	B	1	F5	F1	20	3.59	10.50	476.86	24.76
9	G2	B	1	F4	B	25	4.38	12.00	432.38	24.89
9	G2	B	2	F5	B	70	8.17	12.00	478.86	25.24
9	G2	B	2	F5	B	50	5.20	12.00	460.77	17.78
9	G2	B	3	F8	F2	100	9.43	11.50	510.26	22.67
9	G2	B	2	F5	F2	70	6.90	11.50	455.94	23.37
9	G2	B	3	F8	F1	80	8.05	11.50	461.50	28.89
28	G3	B	2	F5	B	50	7.57	11.50	469.72	28.89
28	G3	B	2	F5	F1	70	6.59	11.50	550.16	22.22
28	G3	B	3	F8	F1	80	9.77	11.50	547.45	28.32
28	G3	B	1	F5	F1	40	5.78	12.50	525.39	26.13
28	G3	B	3	F8	F1	70	7.62	11.50	585.92	33.90
28	G3	B	2	F8	F1	70	9.00	11.50	561.74	37.65
28	G3	B	2	F5	F1	50	7.66	12.00	528.85	26.67
28	G3	B	3	F11	F1	100	10.02	11.00	566.75	33.97
16	G1	B	2	F4	B	50	4.11	11.00	460.76	19.05
16	G1	B	3	F5	F1	110	7.22	11.50	490.17	26.03
16	G1	B	2	F5	B	50	4.82	11.50	492.68	27.37
16	G1	B	2	F4	B	50	5.00	12.00	465.09	20.73
16	G1	B	1	F4	B	15	3.67	11.50	484.45	17.02
16	G1	B	2	F4	B	30	3.80	11.00	455.23	18.51
16	G1	B	3	F5	F2	85	5.72	11.50	485.96	26.32
2	G1	B	1	F4	B	20	3.20	11.50	501.12	13.75
2	G1	B	2	F4	F1	45	3.64	11.50	474.00	17.33
2	G1	B	1	F4	F2	30	3.36	11.00	478.81	21.56
2	G1	B	2	F4	F2	40	3.83	11.50	440.59	20.83
2	G1	B	2	F5	F1	45	5.70	12.00	466.42	20.41
2	G1	B	2	F4	F1	40	4.91	12.50	426.47	22.51
2	G1	B	3	F5	F1	120	6.48	11.50	493.19	23.56
2	G1	T	1	F4	F1	40	4.03	12.00	458.24	20.10
2	G1	T	2	F5	F2	35	4.85	11.00	413.30	20.57

B = butt log; M = middle log; T = top log.
G1 = low stiffness trees; G2 = medium stiffness trees; G3 = high stiffness trees.

APPENDIX 2A: RESULTS OF MODULUS OF ELASTICITY, BENDING STRENGTH AND DENSITY FOR CLEARWOOD SPECIMENS FROM THE BUTT, MIDDLE AND TOP LOGS: A and B represent matching specimens from the same board.

Sample No.	Tree No.	Log type	Position from Pith	Density (kg/cu.m) A	Density (kg/cu.m) B	MOE (GPa) A	MOE (GPa) B	MOR (MPa) A	MOR (MPa) B	Angle of Spiral Grain (Degree)
1	45	T	2	439.36	436.08	6.49	6.06	65.63	65.15	5.50
2	45	T	1	400.56	396.90	4.72	4.45	42.68	42.30	7.50
3	45	T	1	424.60	425.02	5.75	6.20	46.15	48.13	2.50
4	45	T	2	416.72	395.28	7.38	6.42	60.42	55.36	0.00
5	45	T	3	437.93	440.89	11.10	11.49	62.62	62.56	4.50
6	45	T	2	443.83	439.70	7.08	6.64	67.65	67.21	0.00
7	45	T	3	448.59	458.90	8.81	9.14	65.19	64.51	3.50
8	33	T	3	409.32	405.21	6.26	5.85	67.53	66.97	4.50
9	33	T	2	428.82	433.31	7.32	7.48	52.01	52.92	5.00
10	33	T	2	423.39	410.60	6.93	7.44	53.74	55.25	3.50
11	33	T	1	421.65	426.63	5.44	5.08	54.81	54.33	4.25
12	33	T	3	419.94	419.53	7.61	7.54	59.14	58.88	3.75
13	33	T	2	431.24	435.39	7.55	7.80	54.34	54.12	7.91
14	33	T	3	419.21	414.67	9.25	10.55	69.70	67.84	2.50
15	33	T	3	430.45	426.74	8.58	8.95	61.03	60.83	3.38
16	27	T	1	463.45	455.40	6.76	8.59	59.03	59.27	6.50
17	27	T	2	472.10	471.28	8.84	9.69	67.58	68.62	0.00
18	27	T	2	488.16	480.73	6.61	6.75	48.76	48.54	8.94
19	27	T	2	432.73	436.76	8.45	8.28	68.55	68.27	0.00
20	27	T	3	457.57	465.74	9.17	9.87	68.40	67.96	5.50
21	27	T	2	450.43	442.18	7.66	7.33	65.74	65.40	4.00
22	31	M	1	442.92	441.27	6.84	6.45	62.16	61.76	5.25
23	31	M	2	516.01	512.29	8.50	10.52	90.50	90.06	4.00
24	31	M	2	491.17	488.30	7.72	8.46	66.77	66.24	3.50
25	31	M	3	491.59	483.38	10.04	10.85	84.10	82.41	3.00
26	31	M	3	480.93	476.39	9.61	10.88	83.67	84.15	2.50
27	31	M	3	472.72	472.31	12.19	12.01	81.40	81.25	5.86
28	10	M	1	460.78	466.96	7.04	6.73	60.27	59.93	2.50
29	10	M	2	511.00	517.98	8.38	10.52	91.47	88.27	0.00
30	10	M	3	438.05	454.88	9.63	10.78	71.80	71.61	0.00
31	10	M	2	451.60	454.06	7.88	8.41	61.26	60.25	5.48
32	10	M	2	455.79	452.47	9.09	9.17	68.40	68.16	0.00
33	10	M	3	483.19	479.12	10.83	10.60	87.60	87.31	2.25
34	10	M	2	486.26	487.08	6.43	6.05	59.57	59.16	4.25
35	10	M	3	479.69	475.97	11.23	11.17	82.55	80.77	0.00
36	23	T	1	436.77	435.54	7.33	7.78	59.17	54.77	5.00
37	23	T	2	469.67	457.53	9.20	8.84	70.11	68.47	6.39
38	23	T	2	470.52	466.40	7.72	7.22	76.87	76.38	3.75
39	26	T	2	441.41	440.18	6.55	6.12	64.51	64.03	2.75
40	26	T	2	465.33	449.00	9.05	8.99	70.83	71.12	4.81
41	26	T	3	420.22	456.53	8.71	8.76	70.06	68.74	0.00
42	11	T	2	412.97	414.60	7.48	7.48	62.37	62.37	0.00

43	11	T	2	431.61	433.27	7.16	7.16	69.48	69.48	0.00
44	11	T	1	440.75	440.34	6.87	6.87	60.38	60.38	3.01
45	11	T	3	517.16	515.91	9.94	10.05	76.13	76.13	3.50
46	11	T	2	425.28	427.37	8.67	8.67	71.95	71.95	8.50
47	13	T	2	437.54	435.49	5.58	6.61	58.75	54.75	5.50
48	13	T	1	414.89	409.92	7.17	6.83	55.40	54.21	3.00
49	13	T	2	436.81	440.99	8.40	9.19	62.67	61.96	4.25
50	13	T	2	432.26	436.37	6.75	6.32	65.68	65.24	3.75
51	26	T	1	445.43	441.72	6.48	6.35	51.53	51.25	3.75
52	24	T	2	470.44	472.10	8.29	8.29	70.84	70.84	6.75
53	24	T	1	457.50	456.68	6.01	6.01	58.55	58.55	2.75
54	24	T	2	486.95	486.13	7.90	7.90	70.32	70.32	2.75
55	24	T	3	457.52	455.05	11.71	11.70	89.48	89.48	0.00
56	24	T	3	488.36	489.59	10.02	10.04	91.66	91.66	2.50
57	24	T	2	506.23	504.19	8.30	8.30	72.21	72.21	0.00
58	1	T	2	417.48	417.07	6.01	5.68	53.70	53.33	1.30
59	1	T	3	405.83	428.87	7.79	8.89	64.47	63.01	3.91
60	1	T	1	469.12	464.21	6.11	6.96	55.01	57.10	5.25
61	1	T	3	452.92	472.62	9.73	10.73	74.99	75.41	0.00
62	1	T	2	410.11	421.31	8.36	8.95	59.35	59.20	0.00
63	45	M	1	391.85	393.07	5.60	5.54	43.76	43.50	5.48
64	45	M	2	407.11	415.32	6.66	7.32	59.36	56.59	6.25
65	45	M	1	425.68	422.82	6.60	6.81	49.23	49.20	6.45
66	45	M	2	434.32	435.96	6.65	6.26	60.66	60.25	7.29
67	45	M	3	465.16	477.18	7.47	6.99	72.73	72.26	0.00
68	45	M	2	428.07	425.16	6.93	6.48	72.00	71.45	3.00
69	45	M	3	469.37	476.41	9.50	10.43	76.83	75.60	2.00
70	45	M	2	458.86	462.13	8.15	7.90	67.42	67.12	0.00
71	45	M	2	454.24	446.81	6.71	6.34	60.50	60.10	0.00
72	45	M	3	446.28	462.70	9.79	9.71	76.44	76.17	0.00
73	44	T	2	448.19	446.95	6.61	6.28	58.34	57.98	4.00
74	44	T	3	469.12	486.77	8.20	7.77	73.52	73.14	0.00
75	44	T	1	429.07	424.97	6.98	6.66	60.15	59.80	6.37
76	44	T	2	442.31	445.15	8.44	8.77	75.66	73.51	0.00
77	44	T	2	463.06	466.72	7.23	6.76	73.84	73.35	3.00
78	44	T	3	416.28	435.98	9.48	9.58	71.32	71.08	3.00
79	44	T	2	449.32	448.91	8.40	8.52	62.22	61.99	3.25
80	19	M	1	523.46	511.15	5.41	5.68	58.50	59.87	8.73
81	19	M	1	454.58	448.42	5.32	4.97	51.69	51.23	7.25
82	19	M	3	466.41	480.10	8.54	8.02	81.06	80.61	3.75
83	19	M	2	446.54	451.88	6.96	6.95	62.86	60.84	6.75
84	19	M	2	453.27	443.42	9.78	9.90	78.53	78.00	2.75
85	19	M	2	420.69	428.90	6.89	6.53	61.20	60.83	2.83
86	19	M	2	500.92	500.11	8.21	8.10	65.26	64.99	3.50
87	19	M	3	433.82	438.36	9.88	10.94	72.40	72.29	4.65
88	19	M	2	434.61	437.91	8.39	9.07	57.07	56.90	4.50
89	6	T	2	440.24	450.14	7.70	8.46	62.51	61.74	0.00
90	6	T	1	481.42	481.01	6.02	5.63	58.05	57.59	2.75
91	6	T	2	453.69	457.82	7.27	6.75	63.83	62.08	0.00
92	6	T	2	448.83	457.86	6.92	6.57	60.96	60.59	0.00

93	6	T	3	480.65	499.53	8.34	7.90	75.16	74.77	2.25
94	21	M	1	411.80	413.45	6.98	7.98	58.72	57.08	0.00
95	21	M	2	433.17	427.78	5.96	5.57	58.20	57.72	4.75
96	21	M	1	413.99	418.48	8.31	9.16	55.99	55.84	4.00
97	21	M	2	392.46	400.63	8.46	8.16	49.22	48.89	4.50
98	38	M	1	427.98	427.98	5.23	6.22	51.48	53.86	8.31
99	38	M	2	476.85	474.36	6.64	7.51	58.04	59.45	4.00
100	38	M	1	480.47	475.52	6.99	7.06	60.36	56.48	7.00
101	38	M	3	486.01	491.40	10.97	11.53	87.33	86.25	0.00
102	38	M	2	524.51	520.87	6.18	5.98	51.42	51.12	1.90
103	38	M	3	467.90	482.83	9.18	9.05	71.81	71.53	2.50
104	22	M	1	441.94	434.89	6.71	6.35	60.08	59.69	6.90
105	22	M	2	462.86	464.92	7.56	7.49	58.52	58.26	4.75
106	22	M	2	434.06	433.24	8.72	9.06	57.30	58.91	0.00
107	22	M	3	474.74	479.66	10.73	9.64	80.43	78.66	3.75
108	34	M	2	455.68	458.97	7.27	7.81	61.87	60.73	1.50
109	34	M	1	429.19	424.67	6.78	6.54	55.57	55.25	3.75
110	34	M	2	432.36	434.82	8.56	8.45	67.35	67.08	2.50
111	34	M	3	427.42	437.37	9.00	8.79	64.55	61.81	3.50
112	34	M	2	441.31	439.66	8.63	9.61	66.95	63.98	0.00
113	33	M	1	509.85	502.01	5.68	6.58	58.46	59.54	3.50
114	33	M	2	435.10	435.92	7.20	7.52	51.24	51.04	5.32
115	33	M	3	454.07	454.89	10.00	11.36	76.43	76.31	4.50
116	33	M	2	444.01	441.94	7.19	7.15	53.17	56.81	4.00
117	33	M	2	431.97	439.89	10.06	9.63	46.89	46.93	6.70
118	33	M	3	450.31	458.11	9.86	9.83	76.08	75.82	3.50
119	33	M	2	459.45	460.29	7.79	8.79	60.87	62.04	6.43
120	47	M	1	468.96	464.86	7.58	7.93	59.48	61.00	3.00
121	47	M	2	446.90	451.83	8.77	8.51	67.96	67.72	6.86
122	47	M	3	485.50	497.81	10.58	11.13	74.73	74.54	5.15
123	47	M	2	446.78	447.60	6.23	6.44	50.96	52.08	4.00
124	47	M	3	531.88	544.26	10.21	10.94	70.48	70.30	3.39
125	47	M	3	506.98	505.74	11.04	10.88	64.35	64.27	8.75
126	47	M	3	520.93	539.40	9.87	9.75	77.67	77.40	8.00
127	47	M	3	473.50	490.17	9.42	9.81	68.07	67.87	3.04
128	47	M	2	509.81	504.91	8.53	8.22	71.99	71.67	4.75
129	6	M	1	461.77	453.60	6.13	5.73	59.71	59.26	2.50
130	6	M	2	472.12	476.25	6.80	7.34	68.31	67.71	3.75
131	6	M	3	504.93	511.08	7.81	7.35	73.04	72.61	2.50
132	6	M	2	434.05	431.17	7.33	6.37	51.81	54.58	4.04
133	6	M	3	495.69	505.59	8.62	10.76	87.91	87.32	3.75
134	6	M	3	482.34	483.17	7.86	7.36	76.72	76.25	3.13
135	6	M	2	477.07	471.74	7.94	7.52	71.20	70.81	0.00
136	41	M	1	435.88	436.72	7.05	7.05	67.73	67.73	7.50
137	41	M	1	440.76	441.98	6.98	6.98	62.37	62.37	8.50
138	41	M	3	499.37	501.40	11.76	11.84	88.37	88.37	0.00
139	41	M	2	488.15	489.39	9.82	9.82	81.23	81.23	4.75
140	41	M	2	481.25	480.44	9.67	9.67	76.06	76.06	0.00
141	9	M	1	503.79	499.64	5.85	6.34	39.81	39.64	7.62
142	9	M	1	479.65	480.89	7.11	8.35	52.70	54.88	6.75

143	9	M	2	416.27	412.25	7.31	7.25	59.54	57.46	0.00
144	9	M	2	460.44	466.63	8.85	8.41	77.98	77.61	0.00
145	20	M	1	451.19	435.59	7.92	7.68	50.51	52.22	6.95
146	20	M	2	458.07	456.83	7.28	7.90	69.76	66.57	0.00
147	20	M	2	495.59	495.59	8.09	8.04	62.77	62.52	0.00
148	20	M	3	447.14	463.56	9.80	10.07	71.37	70.91	4.42
149	20	M	3	450.53	455.07	8.35	9.21	69.58	67.41	4.50
150	20	M	4	460.27	480.59	10.39	10.40	80.13	79.89	3.01
151	26	M	1	484.20	473.52	6.33	5.91	66.48	65.94	2.00
152	26	M	2	446.58	449.88	7.27	6.92	62.94	62.58	6.95
153	26	M	3	455.19	465.19	10.47	10.60	77.92	77.68	4.00
154	26	M	2	449.17	445.10	8.47	8.55	63.82	63.59	3.00
155	26	M	3	445.34	459.02	9.50	10.62	76.41	74.89	1.75
156	26	M	2	477.04	470.06	6.45	7.41	52.14	54.18	1.80
157	26	M	3	467.70	482.56	10.09	11.36	85.52	84.92	6.26
158	23	M	1	415.80	408.33	7.47	7.58	55.23	55.00	4.25
159	23	M	2	410.48	416.64	8.28	8.06	67.50	67.21	1.00
160	23	M	2	469.43	473.95	5.53	7.15	52.00	55.95	2.52
161	23	M	3	473.34	475.83	10.26	11.18	84.56	84.03	4.10
162	23	M	2	449.37	446.07	9.02	9.93	60.19	59.33	0.00
163	23	M	2	488.87	497.08	9.36	8.95	53.96	53.28	5.48
164	32	M	1	412.51	406.35	5.37	5.98	40.27	42.80	3.00
165	32	M	2	470.86	465.96	7.98	9.20	72.30	71.02	0.00
166	32	M	3	448.24	456.53	10.29	11.07	77.15	76.58	0.00
167	32	M	1	386.22	382.94	8.87	8.05	45.70	45.70	5.15
168	32	M	2	436.12	434.89	8.57	9.41	60.98	62.91	6.00
169	32	M	3	441.83	467.69	9.07	8.68	69.69	68.47	1.49
170	28	M	1	430.43	429.18	5.88	6.00	43.85	46.25	7.50
171	28	M	2	500.50	496.15	8.58	8.76	85.38	81.00	0.00
172	28	M	3	527.83	527.56	11.23	10.18	89.85	89.93	0.00
173	28	M	1	423.69	425.51	6.65	6.63	46.74	45.43	5.03
174	28	M	3	503.27	503.00	9.70	9.82	77.92	77.43	0.00
175	28	M	3	498.87	499.70	10.05	10.65	75.86	76.70	3.25
176	28	M	2	498.49	505.05	11.03	10.75	82.57	83.94	0.00
177	4	M	1	460.49	449.36	7.14	6.99	56.91	56.62	7.00
178	4	M	1	369.73	361.48	9.27	7.59	59.18	59.06	5.50
179	4	M	3	455.62	467.47	10.41	10.51	78.98	78.74	2.75
180	4	M	2	433.81	432.99	8.21	9.37	53.57	53.44	3.50
181	4	M	2	436.71	432.58	8.68	9.00	62.56	62.35	0.00
182	4	M	2	451.49	453.13	7.16	7.10	55.42	55.16	5.00
183	12	M	1	384.44	369.22	6.35	6.28	50.31	50.05	2.80
184	12	M	1	379.00	376.97	6.28	6.44	46.41	46.20	5.25
185	12	M	2	433.15	438.54	6.98	7.32	49.22	49.02	7.00
186	12	M	2	403.92	398.94	6.06	5.92	58.31	56.73	3.75
187	40	M	1	430.10	421.89	6.99	6.73	58.20	57.88	6.18
188	40	M	3	491.17	501.49	11.71	11.39	95.25	94.95	0.00
189	40	M	2	420.09	424.62	8.93	8.02	49.84	50.99	1.80
190	40	M	1	431.52	423.31	6.94	7.23	49.66	49.45	4.85
191	40	M	2	436.95	429.97	9.10	9.24	67.17	66.94	5.55
192	25	M	1	429.35	426.84	6.54	6.27	45.96	52.68	5.75

193	25	M	2	416.51	419.14	7.88	7.59	61.90	58.43	4.75
194	25	M	2	428.14	429.63	7.42	7.82	64.17	63.55	3.25
195	25	M	3	485.37	482.35	9.41	9.50	80.26	81.56	0.00
196	25	M	2	462.69	464.66	8.89	9.08	81.58	77.37	0.00
197	25	M	2	435.94	432.07	7.57	8.26	63.42	64.58	0.00
198	16	M	1	472.73	473.54	5.39	5.19	57.60	58.46	6.75
199	16	M	2	434.25	433.83	6.16	5.39	57.19	57.19	0.00
200	16	M	3	545.23	551.07	7.68	6.77	82.56	80.67	5.39
201	16	M	2	462.29	441.52	7.05	6.32	60.37	64.63	2.70
202	16	M	3	550.83	554.23	9.87	9.67	67.36	67.55	4.83
203	16	M	2	483.26	483.54	8.88	7.57	79.81	84.50	3.00
204	5	M	1	479.63	473.60	5.32	5.34	56.87	61.81	4.00
205	5	M	2	493.69	495.35	6.47	6.45	62.16	67.51	7.50
206	5	M	3	504.31	501.95	8.36	7.91	77.93	81.52	3.82
207	5	M	3	539.14	539.56	9.27	10.47	79.54	81.74	0.00
208	5	M	1	451.77	452.48	6.35	5.79	56.35	56.83	4.51
209	5	M	2	445.98	451.68	5.98	6.50	61.36	65.00	5.50
210	5	M	2	473.02	477.40	7.11	7.78	51.98	53.47	6.45
211	5	M	2	492.44	477.23	8.16	7.61	72.76	64.83	3.00
212	5	M	2	499.01	479.71	7.31	7.65	69.12	72.60	4.85
213	5	M	2	529.56	516.10	8.47	11.25	60.74	72.64	0.00
214	5	M	3	507.67	506.97	9.35	7.92	83.04	61.27	1.75
215	36	M	1	484.34	480.24	6.79	6.55	56.29	55.98	8.00
216	36	M	2	452.43	450.35	8.58	8.50	64.24	61.56	3.01
217	36	M	3	442.94	452.34	9.34	8.99	79.03	78.71	3.00
218	36	M	2	442.94	445.41	7.53	7.59	56.51	56.27	5.27
219	36	M	3	449.46	456.09	10.37	10.02	85.50	85.18	0.00
220	36	M	3	444.37	452.54	9.91	10.80	77.97	77.67	0.00
221	36	M	2	450.45	456.55	8.68	9.04	62.35	62.15	0.00
222	37	M	1	478.46	467.32	6.89	6.68	56.13	55.83	5.25
223	37	M	2	523.17	514.84	8.01	7.49	79.71	79.20	5.50
224	37	M	3	524.96	534.04	10.42	9.98	89.25	88.91	0.00
225	37	M	2	445.59	442.33	8.52	8.61	64.10	63.86	0.00
226	37	M	2	525.64	529.78	10.17	10.42	63.20	63.64	1.25
227	37	M	3	469.48	477.82	8.92	8.42	80.15	79.74	2.50
228	37	M	3	518.90	520.95	10.76	10.91	80.69	80.45	5.25
229	27	M	2	433.61	422.00	7.57	7.49	58.78	58.50	7.08
230	27	M	2	448.57	445.70	8.47	8.88	60.28	60.09	4.50
231	27	M	1	442.18	441.78	6.37	6.20	52.44	52.15	2.25
232	27	M	2	478.30	476.65	8.50	7.15	46.22	46.19	1.50
233	27	M	3	468.17	479.20	9.62	9.88	78.12	77.63	0.00
234	27	M	3	468.36	470.84	9.79	9.82	74.31	74.06	4.00
235	27	M	2	443.44	441.79	8.22	9.48	53.22	53.08	4.00
236	11	M	1	431.70	428.69	6.88	6.55	64.74	62.75	0.00
237	11	M	2	425.97	440.00	8.53	8.97	59.28	68.74	2.75
238	11	M	2	457.80	461.75	10.03	9.51	73.16	67.27	0.00
239	11	M	2	436.52	434.59	7.67	7.87	60.96	67.99	0.00
240	11	M	3	471.65	475.96	10.35	9.61	71.56	63.08	0.00
241	11	M	3	432.02	433.83	12.65	12.44	61.43	59.22	0.00
242	18	M	1	433.26	424.28	5.49	5.59	41.58	51.90	2.50

243	18	M	1	435.11	433.42	5.45	5.25	59.33	67.59	1.00
244	18	M	3	470.34	465.26	11.07	9.49	74.67	75.29	0.00
245	18	M	2	463.75	460.12	8.44	6.60	70.02	72.97	6.00
246	18	M	3	471.21	474.15	9.76	8.41	72.01	72.20	4.75
247	18	M	2	454.82	445.14	9.90	8.55	73.08	70.98	0.00
248	18	M	4	482.53	484.21	11.88	9.28	61.15	58.86	2.75
249	18	M	2	418.11	434.20	8.10	7.24	70.10	70.12	0.00
250	18	M	3	492.39	496.16	6.36	6.14	75.15	65.03	3.69
251	30	M	1	426.88	415.50	6.41	6.02	60.21	59.79	3.25
252	30	M	2	441.86	439.38	6.63	6.31	58.09	57.73	2.00
253	30	M	1	406.28	407.93	7.24	7.16	56.39	56.12	2.50
254	30	M	2	430.23	429.00	8.53	9.44	57.26	57.11	4.00
255	30	M	3	451.12	456.81	11.37	11.57	85.07	84.85	0.00
256	15	M	1	427.02	418.77	6.64	6.31	58.10	57.73	5.00
257	15	M	2	471.86	463.57	7.93	7.43	76.41	75.94	0.00
258	15	M	3	457.17	466.25	10.71	11.06	77.15	76.93	4.25
259	15	M	2	445.21	441.49	8.37	9.01	57.77	57.59	3.00
260	15	M	3	482.51	483.73	11.75	12.35	83.68	83.48	3.75
261	15	M	3	479.15	482.02	10.27	10.07	82.22	81.94	1.50
262	15	M	2	476.24	471.73	9.34	8.87	83.17	82.80	4.25
263	15	M	2	428.38	430.45	9.26	9.14	65.36	63.75	4.50
264	15	M	3	490.89	498.76	8.96	10.28	84.61	83.53	0.00
265	14	M	1	503.02	496.04	6.51	6.08	66.03	65.53	2.50
266	14	M	2	479.86	477.39	7.38	6.96	67.58	67.17	2.50
267	14	M	2	460.51	456.00	7.73	7.36	67.02	66.66	0.00
268	14	M	2	431.22	439.10	7.23	7.04	58.04	57.73	4.27
269	14	M	2	476.32	469.62	7.46	6.99	70.89	70.42	1.25
270	43	M	1	424.54	413.81	6.30	6.30	55.87	53.23	4.60
271	43	M	2	447.85	444.53	7.29	8.48	59.14	60.36	7.75
272	43	M	3	490.10	494.59	9.89	11.07	79.75	79.53	2.50
273	43	M	2	450.11	445.96	9.02	8.96	69.59	69.32	7.06
274	43	M	3	471.43	474.71	9.51	9.26	77.56	77.27	3.75
275	43	M	2	501.77	501.36	9.36	11.30	83.62	83.30	4.00
276	48	M	2	469.04	471.52	7.58	7.09	77.39	76.88	0.00
277	48	M	3	415.62	423.38	9.33	9.29	72.26	72.01	1.25
278	48	M	1	407.93	400.05	6.10	6.89	54.79	56.83	1.50
279	48	M	2	454.70	458.82	7.12	6.65	71.25	70.76	0.00
280	48	M	2	474.84	470.73	8.22	7.73	77.69	77.27	0.00
281	29	M	1	441.85	432.73	6.20	5.83	72.05	71.36	5.90
282	29	M	2	424.20	433.23	8.29	10.01	51.88	51.77	0.00
283	29	M	3	447.48	460.95	9.10	9.38	63.91	62.49	4.50
284	29	M	2	476.17	472.88	7.41	8.18	49.78	49.63	5.13
285	29	M	3	542.86	545.73	11.33	11.02	93.11	92.81	3.75
286	42	M	3	476.18	480.74	10.14	9.91	81.22	80.92	2.25
287	42	M	2	446.76	450.08	9.30	10.86	68.91	68.35	4.75
288	42	M	1	458.64	447.50	6.19	5.86	55.95	55.57	4.65
289	42	M	3	446.20	458.98	8.62	8.39	69.86	69.56	3.50
290	42	M	2	448.31	444.19	7.95	7.96	46.22	46.15	8.62
291	44	M	1	463.21	453.46	7.13	6.84	60.66	60.33	6.75
292	44	M	2	478.38	480.01	8.34	8.22	65.61	65.34	8.25

293	44	M	3	464.79	473.45	7.43	6.97	82.63	82.03	3.00
294	44	M	2	491.76	485.60	9.33	9.00	78.00	77.68	0.00
295	44	M	2	486.48	485.64	8.69	8.20	78.77	78.36	2.50
296	44	M	2	389.42	394.40	7.72	7.38	58.78	55.24	2.00
297	44	M	3	463.25	472.74	9.10	8.82	74.72	74.41	1.50
298	24	M	1	465.52	467.59	8.02	8.91	65.90	71.35	4.03
299	24	M	2	504.22	508.43	9.42	9.65	69.52	76.02	0.00
300	24	M	3	546.66	537.49	10.38	10.67	81.29	80.82	0.00
301	24	M	3	583.67	580.77	11.00	9.90	71.46	63.68	0.00
302	24	M	2	497.29	490.34	8.62	8.78	75.42	73.06	0.00
303	35	M	1	449.68	435.65	6.38	5.99	60.10	59.68	0.00
304	35	M	2	432.18	432.18	7.13	6.74	63.43	63.04	5.00
305	35	M	2	430.34	435.65	7.61	8.10	63.62	64.00	5.41
306	35	M	3	472.68	480.11	9.55	9.93	80.67	80.43	0.00
307	35	M	3	465.45	469.55	9.98	10.48	78.43	77.84	0.00
308	35	M	2	444.66	439.75	7.36	7.17	59.77	59.47	4.00
309	35	M	3	490.57	497.88	10.71	10.35	89.71	89.40	1.75
310	39	M	1	459.82	453.22	6.25	7.52	60.32	60.57	4.50
311	39	M	2	454.72	454.72	7.73	7.45	64.66	64.34	2.66
312	39	M	3	476.74	479.63	10.51	10.56	88.74	88.65	3.25
313	39	M	3	441.49	450.47	8.74	10.09	73.30	74.19	0.00
314	39	M	2	436.98	432.00	8.56	8.89	61.13	60.92	6.41
315	39	M	3	462.23	464.28	11.81	11.58	85.91	85.70	2.50
316	13	M	1	409.00	397.28	6.53	6.29	54.17	53.85	3.75
317	13	M	2	418.16	416.53	7.32	6.87	69.65	69.23	0.00
318	13	M	3	416.42	428.44	9.28	9.29	70.40	70.15	3.54
319	13	M	2	432.09	429.62	7.64	7.43	62.05	61.74	5.40
320	13	M	3	434.76	435.58	9.34	8.97	79.36	79.02	0.00
321	13	M	2	414.88	412.81	9.02	9.46	63.93	63.73	1.59
322	13	M	2	418.58	420.66	9.01	10.07	59.40	59.24	2.50
323	13	M	3	432.31	435.16	9.76	10.72	77.00	75.47	0.00
324	46	M	1	450.57	449.33	6.44	6.24	52.77	52.46	8.25
325	46	M	2	453.83	455.06	9.65	8.84	70.37	68.62	4.51
326	46	M	2	495.32	494.49	6.86	6.46	62.67	62.25	2.00
327	46	M	1	429.29	425.14	6.28	6.06	52.05	51.74	2.75
328	17	M	2	410.36	414.02	7.02	7.02	53.73	53.49	5.50
329	17	M	1	425.66	423.57	6.72	6.55	46.71	49.16	5.00
330	17	M	2	466.98	464.88	6.87	6.51	60.50	60.12	9.30
331	17	M	2	462.80	464.46	8.92	9.60	61.02	60.84	4.00
332	17	M	2	451.60	448.31	8.98	9.31	65.05	64.84	6.75
333	8	M	1	478.79	477.96	7.19	8.48	68.93	66.17	0.00
334	8	M	2	441.50	443.97	9.18	10.06	64.63	65.39	5.00
335	8	M	2	458.25	454.54	6.05	5.69	55.77	55.35	6.75
336	8	M	2	478.39	476.75	9.32	10.73	75.49	75.78	0.00
337	1	M	2	445.26	446.50	8.86	9.17	58.18	58.75	0.00
338	1	M	1	438.56	436.51	6.42	6.22	52.68	52.38	5.49
339	1	M	1	430.61	431.01	5.61	5.37	47.48	47.16	3.25
340	1	M	2	454.36	457.66	6.38	7.99	60.71	62.03	4.50
341	1	M	2	435.83	434.22	8.43	8.75	64.59	65.48	4.50
342	7	M	2	491.47	490.22	7.76	7.58	73.61	71.80	3.75

343	7	M	2	487.33	483.20	7.74	8.03	55.91	55.71	3.00
344	7	M	1	437.83	436.18	7.17	6.86	61.32	60.98	0.00
345	7	M	2	456.90	457.72	9.59	10.17	67.77	67.59	4.25
346	2	M	1	429.38	428.96	5.82	4.11	51.65	49.80	2.75
347	2	M	2	438.76	427.96	5.53	5.12	52.39	65.70	4.93
348	2	M	2	410.60	411.56	5.93	5.28	64.99	72.64	8.00
349	3	M	1	580.02	571.65	7.50	8.90	75.26	74.41	5.13
350	3	M	2	518.66	521.16	11.28	10.21	68.49	72.18	0.00
351	3	M	3	533.71	537.38	12.02	10.95	86.08	66.07	4.74
352	3	M	1	481.31	485.91	4.85	5.86	37.17	51.41	10.45
353	3	M	2	481.35	475.65	8.77	9.59	60.63	72.00	0.00
354	3	M	2	502.77	506.09	11.04	10.18	82.96	74.77	3.02
355	3	M	2	507.62	490.50	9.21	7.59	67.24	56.58	2.00
356	36	B	1	452.70	447.75	6.29	7.65	57.95	56.86	0.00
357	36	B	2	449.22	447.98	7.95	7.72	65.05	64.74	3.50
358	36	B	1	464.54	461.68	6.06	5.66	60.24	59.76	1.30
359	36	B	2	449.93	445.35	6.15	5.75	60.77	60.29	2.75
360	36	B	3	474.79	476.84	9.23	9.83	76.34	75.25	0.00
361	36	B	2	484.10	481.61	8.41	7.79	62.17	59.86	3.35
362	36	B	2	444.88	440.78	8.33	8.06	68.57	68.26	0.00
363	36	B	2	463.49	466.36	9.32	9.09	75.44	75.15	4.00
364	17	B	1	453.97	451.11	6.30	5.65	57.68	57.54	0.00
365	17	B	3	438.31	449.81	7.08	6.68	64.60	64.19	0.00
366	17	B	2	460.90	458.45	6.76	6.32	66.60	66.13	3.00
367	17	B	3	479.29	481.34	8.62	8.14	78.79	78.40	0.00
368	17	B	3	439.48	441.95	8.45	8.19	68.83	68.52	2.50
369	17	B	2	433.61	435.27	7.49	8.12	56.91	56.55	4.25
370	15	B	1	455.24	453.20	4.78	4.45	48.66	48.16	4.00
371	15	B	2	462.19	463.02	5.59	5.75	62.69	63.39	0.00
372	15	B	3	516.09	517.73	9.55	10.63	87.60	87.37	3.00
373	15	B	1	439.07	437.43	5.26	5.89	51.61	54.93	4.00
374	15	B	2	485.96	484.73	7.75	9.27	57.11	56.97	2.00
375	15	B	3	533.33	537.41	9.68	9.11	91.88	91.45	0.00
376	15	B	3	510.26	518.55	9.78	9.55	78.34	78.05	0.00
377	15	B	2	495.37	493.72	7.03	7.07	49.79	50.63	5.75
378	15	B	2	439.15	440.37	7.18	7.59	50.83	50.65	1.90
379	15	B	2	478.93	479.34	10.24	10.87	63.54	63.44	3.00
380	46	B	1	440.09	438.86	5.90	5.83	46.21	45.94	9.25
381	46	B	2	448.98	448.15	7.54	7.57	61.63	61.57	0.00
382	46	B	3	478.62	486.95	9.83	9.95	72.99	72.75	3.25
383	46	B	1	433.34	428.76	5.15	4.80	53.80	53.25	3.50
384	46	B	3	451.32	457.45	9.52	9.68	71.09	70.86	2.16
385	46	B	2	494.65	493.84	8.91	8.54	76.77	76.43	5.00
386	46	B	2	500.04	500.45	8.81	8.16	51.30	53.01	9.42
387	46	B	3	481.04	485.62	8.59	8.25	72.04	71.70	3.90
388	38	B	1	432.15	427.15	5.05	4.70	53.07	52.53	8.05
389	38	B	2	445.14	444.33	6.72	6.40	58.34	57.99	4.75
390	38	B	1	444.02	441.58	5.22	4.87	57.31	56.75	0.00
391	38	B	3	467.95	472.08	9.50	9.52	72.13	71.88	2.75
392	38	B	2	484.42	486.47	6.89	7.42	60.74	61.07	3.25

393	38	B	2	483.59	481.93	8.33	7.80	81.55	81.07	3.50
394	4	B	1	477.29	470.27	5.88	5.48	60.55	60.02	0.00
395	4	B	2	446.31	445.91	7.84	7.46	69.40	69.04	0.00
396	4	B	3	523.42	525.51	10.62	10.20	90.22	89.88	0.00
397	4	B	2	466.99	466.58	7.23	6.79	68.57	68.14	0.00
398	4	B	3	495.83	498.69	10.93	10.61	90.15	89.84	0.00
399	4	B	2	471.12	470.29	8.62	7.24	53.20	53.10	3.18
400	4	B	3	497.26	505.47	9.52	9.90	92.16	90.10	0.00
401	5	B	1	485.07	490.49	4.12	4.12	58.07	52.63	6.64
402	5	B	2	420.05	433.59	4.82	4.64	49.74	65.23	4.00
403	5	B	3	547.82	543.07	7.83	6.05	75.30	65.31	2.50
404	5	B	2	565.85	562.86	4.14	4.19	61.60	64.88	0.00
405	5	B	2	633.65	638.23	4.46	4.72	63.79	63.99	7.11
406	5	B	4	572.19	573.18	6.66	9.18	64.11	70.55	5.46
407	5	B	3	542.03	544.98	6.76	7.30	80.08	77.98	1.75
408	5	B	3	572.61	567.56	6.52	6.58	73.76	73.12	1.50
409	5	B	3	552.59	541.71	7.02	6.58	74.03	67.74	2.25
410	5	B	2	495.12	494.02	6.12	6.05	61.39	58.50	0.00
411	5	B	3	550.64	537.80	5.53	6.85	69.04	80.18	5.96
412	5	B	4	575.00	569.75	9.90	8.89	98.53	95.40	0.00
413	5	B	2	513.64	533.02	5.59	5.20	59.62	61.81	5.35
414	13	B	1	445.82	440.90	4.57	4.26	50.22	49.63	2.00
415	13	B	2	463.02	466.31	6.48	6.13	58.44	58.06	0.00
416	13	B	2	447.46	449.12	7.48	8.05	59.46	60.70	1.50
417	13	B	4	479.15	491.47	11.04	10.27	90.26	86.75	2.51
418	13	B	2	424.12	417.90	5.97	5.59	67.07	66.46	5.50
419	13	B	3	450.32	458.57	9.61	10.87	80.11	80.27	1.00
420	13	B	1	483.48	479.79	6.00	6.00	45.95	45.70	3.75
421	13	B	1	481.01	477.72	8.41	8.02	72.71	72.36	5.49
422	13	B	3	455.08	456.73	9.10	8.68	78.91	78.55	2.75
423	13	B	3	489.96	497.68	8.58	9.36	70.41	70.16	1.20
424	13	B	2	488.29	485.80	7.97	7.61	68.34	67.98	4.45
425	20	B	1	497.47	490.49	6.06	5.66	58.76	58.30	4.25
426	20	B	2	492.52	492.52	6.86	6.41	66.82	66.35	3.75
427	20	B	3	490.36	491.59	10.56	10.53	81.27	81.01	1.75
428	20	B	2	472.68	468.96	5.59	6.18	47.95	49.35	2.00
429	20	B	3	499.70	505.86	9.40	8.95	82.58	82.22	4.00
430	20	B	2	463.33	460.84	9.35	9.22	73.09	72.81	1.50
431	20	B	2	456.64	455.41	8.17	8.78	56.78	56.60	6.00
432	20	B	3	503.39	505.41	11.15	11.25	73.25	73.12	0.00
433	20	B	3	514.83	521.40	10.36	10.04	85.55	85.24	0.00
434	20	B	4	544.82	551.32	11.44	10.94	99.76	99.41	1.24
435	20	B	3	514.29	517.14	12.79	12.21	89.76	89.59	5.50
436	10	B	1	470.22	460.01	6.04	5.64	62.39	61.87	3.50
437	10	B	2	461.48	465.21	7.32	6.80	61.49	62.24	2.25
438	10	B	3	512.66	515.93	9.44	8.88	89.08	88.65	2.25
439	10	B	1	450.41	445.39	6.97	7.44	67.38	68.83	0.00
440	10	B	2	442.25	442.25	6.51	6.55	49.33	49.08	3.50
441	10	B	3	449.45	446.58	6.66	6.37	65.62	62.76	0.00
442	10	B	2	473.73	468.83	7.64	7.75	57.33	57.11	5.00

443	10	B	3	505.43	507.90	8.76	8.28	79.68	79.28	3.50
444	10	B	3	519.88	520.71	10.26	9.67	94.54	94.12	0.00
445	10	B	3	487.34	489.40	10.09	9.72	84.49	84.17	3.25
446	10	B	3	490.70	491.12	9.11	8.97	71.82	71.54	0.00
447	22	B	1	470.25	464.15	4.24	3.98	51.86	51.17	4.00
448	22	B	2	487.31	488.97	5.80	5.41	57.37	56.88	4.42
449	22	B	3	564.07	565.71	8.91	8.38	84.41	83.99	3.75
450	22	B	2	503.66	502.83	6.31	6.14	89.68	88.73	2.75
451	22	B	3	559.34	560.16	7.89	6.28	64.15	63.74	2.00
452	22	B	2	474.95	470.86	8.83	9.59	60.38	60.21	0.00
453	22	B	2	484.64	483.82	7.37	7.16	60.07	59.78	5.50
454	33	B	1	432.37	430.73	5.03	4.71	57.27	56.64	0.00
455	33	B	2	494.60	495.42	7.79	7.32	74.17	73.75	4.25
456	33	B	2	443.87	443.46	9.07	9.30	57.75	57.63	6.19
457	33	B	2	457.98	459.62	8.13	7.71	72.76	72.39	3.00
458	33	B	3	486.89	490.95	8.84	9.44	74.19	72.93	4.00
459	33	B	2	442.01	442.42	7.17	6.85	61.47	61.12	0.00
460	33	B	1	512.32	504.93	5.73	5.36	53.97	53.53	0.00
461	33	B	3	483.69	490.39	8.73	8.21	82.04	81.59	2.75
462	33	B	3	464.78	467.28	9.88	9.69	77.97	77.68	0.00
463	33	B	4	486.22	496.08	11.17	11.11	86.37	86.11	0.00
464	31	B	1	461.26	450.64	6.31	5.52	64.39	60.71	0.00
465	31	B	2	434.71	433.50	5.73	5.50	48.51	48.19	1.30
466	31	B	3	541.91	545.58	8.82	8.37	79.03	78.66	3.25
467	31	B	2	491.05	490.64	9.05	7.53	78.18	77.12	0.00
468	31	B	2	460.40	460.40	10.02	8.04	57.16	57.10	5.94
469	31	B	3	510.00	513.28	10.11	9.99	79.61	79.34	0.00
470	30	B	1	423.43	419.39	6.62	6.25	60.19	59.80	3.50
471	30	B	2	435.34	434.92	5.89	5.49	60.24	59.71	0.00
472	30	B	3	449.09	449.09	8.46	8.14	72.08	71.76	0.00
473	30	B	2	450.22	450.22	8.11	8.74	68.84	67.03	5.59
474	30	B	2	480.39	480.39	8.22	7.96	67.05	66.74	4.00
475	30	B	2	484.88	484.88	9.22	8.79	74.62	74.21	0.00
476	30	B	3	466.95	466.95	10.05	9.64	85.48	85.14	0.00
477	40	B	1	508.99	508.99	5.74	5.97	52.07	52.07	3.50
478	40	B	2	436.41	436.41	8.72	10.30	54.86	54.74	2.89
479	40	B	1	460.92	460.92	4.66	4.36	53.63	52.98	3.75
480	40	B	2	443.10	443.10	6.44	6.19	54.57	54.25	6.72
481	40	B	3	516.94	516.94	9.64	9.69	87.90	87.64	0.00
482	40	B	2	442.04	442.04	8.60	6.96	53.35	52.41	3.96
483	40	B	3	480.23	480.23	10.89	10.47	92.72	92.40	0.00
484	42	B	1	442.14	442.14	6.03	5.63	65.18	64.61	0.00
485	42	B	1	442.72	442.72	6.43	6.07	58.66	58.27	4.50
486	42	B	2	431.13	431.13	7.93	7.97	60.28	60.04	1.00
487	42	B	1	474.07	474.07	5.19	4.84	57.11	56.54	4.50
488	42	B	3	499.74	499.74	8.74	9.14	62.18	61.98	4.03
489	42	B	3	464.01	464.01	9.36	9.63	69.17	68.96	3.50
490	42	B	2	439.80	439.80	7.37	7.40	56.27	56.03	1.00
491	42	B	3	463.76	463.76	9.34	9.40	70.94	70.70	3.40
492	39	B	2	474.10	474.10	7.30	6.88	67.77	67.36	4.25

493	39	B	3	468.44	468.44	8.03	7.96	64.69	62.75	4.75
494	39	B	1	468.68	468.68	7.28	7.15	57.87	57.60	3.50
495	39	B	2	502.91	502.91	6.18	6.60	42.55	42.36	7.00
496	39	B	3	516.25	516.25	9.26	8.77	83.90	83.52	0.00
497	39	B	3	493.47	493.47	8.70	8.18	82.07	81.64	3.00
498	39	B	2	437.15	437.15	8.02	9.06	53.12	52.98	4.00
499	35	B	1	499.07	499.07	4.68	4.37	52.85	52.23	6.25
500	35	B	1	509.67	509.67	5.01	4.72	61.12	60.40	0.00
501	35	B	3	541.57	541.57	9.27	8.68	94.89	94.38	0.00
502	35	B	1	379.12	379.12	11.55	8.80	46.41	46.53	1.15
503	35	B	3	517.80	517.80	9.92	9.48	86.59	86.24	0.00
504	35	B	3	479.30	479.30	10.94	10.77	86.27	86.00	0.00
505	35	B	2	508.66	508.66	7.19	6.76	66.63	66.21	5.25
506	35	B	2	506.15	506.15	8.16	7.74	71.68	71.30	1.00
507	35	B	2	471.24	471.24	9.15	9.93	55.38	55.28	5.48
508	37	B	1	542.09	542.09	3.46	3.36	51.61	50.65	3.00
509	37	B	1	551.07	551.07	4.39	4.40	51.32	55.25	6.25
510	37	B	2	526.30	526.30	8.88	8.90	67.59	67.35	3.00
511	37	B	1	464.54	464.54	4.64	4.32	48.60	48.08	6.00
512	37	B	3	501.96	501.96	9.95	9.50	86.89	86.54	0.00
513	37	B	3	535.97	535.97	9.92	10.06	88.01	86.26	0.00
514	37	B	2	470.73	470.73	5.64	5.52	45.51	45.23	8.00
515	37	B	3	501.08	501.08	10.57	10.64	80.70	80.46	0.00
516	37	B	4	573.31	573.31	10.50	9.92	97.14	96.74	2.50
517	25	B	2	430.11	434.04	7.11	7.69	62.20	75.23	6.50
518	25	B	2	505.31	510.14	9.32	8.28	73.03	65.16	2.00
519	25	B	1	450.32	449.90	7.31	6.73	67.25	63.45	5.06
520	25	B	2	493.26	478.27	7.87	7.49	53.84	59.76	0.00
521	25	B	3	493.24	505.39	8.84	9.13	75.88	71.30	0.00
522	25	B	2	453.78	452.53	9.18	9.87	71.02	69.83	0.00
523	25	B	4	478.51	477.67	9.41	10.27	80.26	81.04	0.00
524	25	B	3	526.66	530.99	9.88	9.84	80.57	74.10	3.00
525	25	B	4	515.66	514.14	10.26	9.66	86.61	74.04	0.00
526	5	T	1	480.57	483.21	5.70	5.78	56.12	56.62	3.55
527	5	T	1	498.42	500.95	5.48	5.69	54.25	60.52	6.75
528	5	T	2	504.23	504.23	7.60	6.88	67.54	63.79	2.00
529	5	T	2	472.23	471.80	6.42	6.34	56.17	63.69	0.00
530	5	T	2	473.09	474.33	8.75	8.56	69.90	67.94	2.25
531	5	T	2	496.96	497.81	7.58	7.74	63.95	65.42	6.15
532	5	T	3	482.48	480.09	7.10	7.52	64.49	72.24	4.75
533	5	T	3	515.14	518.10	7.17	7.97	61.81	61.81	4.00
534	22	T	1	440.47	440.47	5.79	6.70	53.94	54.75	3.00
535	22	T	2	496.75	496.75	9.12	9.19	69.30	69.06	2.25
536	22	T	2	442.85	442.85	9.17	9.82	72.57	69.34	0.00
537	17	T	1	508.99	508.99	5.57	5.41	45.21	44.91	3.25
538	17	T	2	432.95	432.95	7.11	7.84	60.18	57.70	1.89
539	17	T	2	456.89	456.89	8.40	7.90	79.54	79.12	0.00
540	17	T	3	427.66	427.66	9.14	9.58	65.50	65.30	2.50
541	4	T	1	455.84	455.84	7.05	7.05	53.46	53.21	2.25
542	4	T	2	438.33	438.33	8.30	9.03	56.41	56.24	7.75

543	4	T	2	435.44	435.44	8.17	7.88	67.67	67.35	0.00
544	4	T	2	503.62	503.62	7.81	7.34	72.85	72.41	0.00
545	41	T	1	471.91	473.16	6.55	6.55	70.88	70.88	2.75
546	41	T	2	482.76	481.92	8.38	8.38	77.30	77.30	1.75
547	41	T	3	525.47	529.84	11.18	11.20	96.45	96.45	3.75
548	41	T	2	495.17	496.42	8.45	8.45	73.45	73.45	3.25
549	41	T	2	481.82	480.57	8.54	8.54	74.03	74.03	2.75
550	43	T	1	458.38	458.38	5.90	5.51	58.55	58.08	7.25
551	43	T	2	426.57	426.57	8.51	8.73	62.62	62.40	4.25
552	43	T	2	449.57	449.57	7.75	7.53	62.55	62.24	0.00
553	43	T	3	483.60	483.60	10.13	10.67	67.74	66.19	4.39
554	40	T	1	429.89	429.89	7.57	7.28	63.53	63.20	4.59
555	40	T	2	448.92	448.92	7.03	7.70	61.74	59.67	0.00
556	40	T	2	491.07	491.07	6.03	5.68	54.91	54.51	3.00
557	40	T	2	447.37	447.37	7.33	7.43	54.55	54.31	3.25
558	32	T	1	393.58	393.58	6.91	7.73	45.96	45.81	4.25
559	32	T	2	479.19	479.19	6.60	7.69	56.58	58.16	3.75
560	32	T	1	399.28	399.28	7.38	7.30	57.22	56.95	3.70
561	32	T	2	448.91	448.91	7.29	7.18	50.14	50.29	3.00
562	32	T	2	415.69	415.69	8.37	8.34	65.01	64.76	0.00
563	20	T	1	438.51	438.51	6.28	5.78	46.20	45.97	4.70
564	20	T	2	440.92	440.92	8.64	8.51	67.71	67.43	5.75
565	20	T	2	453.30	453.30	9.20	8.88	76.89	76.57	0.00
566	20	T	3	464.05	464.05	9.95	9.81	78.63	78.36	0.00
567	20	T	2	417.35	417.35	9.41	9.45	71.65	71.41	0.00
568	20	T	2	463.67	463.67	9.11	9.34	66.40	66.18	6.95
569	14	T	1	517.62	517.62	6.78	6.38	62.98	62.57	2.00
570	14	T	1	490.54	490.54	6.39	5.97	64.20	63.69	2.75
571	14	T	2	484.71	484.71	4.97	4.63	52.02	51.47	4.51
572	29	T	2	465.83	465.83	8.78	9.43	61.37	61.19	0.00
573	29	T	2	504.10	504.10	9.31	8.89	80.82	80.47	0.00
574	29	T	2	464.78	464.78	7.75	8.38	53.25	53.08	5.50
575	29	T	1	438.68	438.68	7.71	7.63	60.79	60.52	4.00
576	15	T	1	403.53	403.53	7.12	7.07	55.37	55.11	4.00
577	15	T	2	444.75	444.75	8.37	8.07	70.27	69.95	4.50
578	15	T	2	469.92	469.92	8.96	9.21	49.73	51.92	7.27
579	15	T	3	459.95	459.95	9.10	9.14	69.41	69.16	2.75
580	15	T	2	501.13	501.13	7.45	6.99	71.87	71.42	0.00
581	15	T	2	447.12	447.12	8.07	7.67	57.95	58.00	3.26
582	8	T	1	479.03	479.03	7.68	7.26	68.90	68.51	0.00
583	8	T	2	451.91	451.91	6.83	8.06	57.27	58.85	4.00
584	8	T	2	511.55	511.55	7.49	7.04	71.01	70.59	0.00
585	19	T	1	517.31	517.31	5.60	5.23	55.12	54.62	6.49
586	19	T	2	499.16	499.16	7.28	6.97	61.64	61.30	3.75
587	19	T	3	416.72	416.72	8.62	8.21	74.95	74.58	0.00
588	19	T	2	438.55	438.55	7.15	6.70	55.57	54.31	3.00
589	19	T	2	445.97	445.97	7.70	7.32	68.49	68.13	4.00
590	19	T	2	417.90	417.90	6.57	6.43	52.27	51.99	3.50
591	12	T	1	424.85	424.85	10.06	8.24	56.50	56.46	0.00
592	12	T	2	391.16	391.16	7.06	7.17	52.93	52.70	1.20

593	12	T	2	438.69	438.69	11.42	12.47	78.08	77.33	0.00
594	37	T	2	463.03	463.03	8.16	8.61	57.63	57.44	3.75
595	37	T	3	488.12	488.12	9.85	9.53	81.16	80.84	2.51
596	37	T	1	527.63	527.63	5.88	5.51	55.11	54.67	6.25
597	37	T	1	447.06	447.06	5.92	5.59	53.15	52.77	4.54
598	37	T	2	481.10	481.10	8.72	10.24	55.32	55.20	3.75
599	37	T	3	476.27	476.27	9.26	8.95	77.41	77.10	3.00
600	25	T	1	468.20	467.35	6.83	5.97	58.22	61.88	3.00
601	25	T	2	467.26	468.09	8.26	7.98	72.29	71.03	0.00
602	25	T	3	449.06	457.25	9.35	8.88	68.38	64.35	6.50
603	25	T	2	436.08	442.85	8.28	7.50	72.84	66.92	0.00
604	25	T	2	433.11	444.77	9.14	8.58	67.41	60.69	0.00
605	47	T	1	461.89	456.99	6.94	6.49	69.20	68.72	4.50
606	47	T	2	441.84	443.88	8.88	9.16	71.28	69.50	4.75
607	47	T	3	480.58	483.83	8.48	8.14	72.46	72.13	2.25
608	47	T	2	515.18	511.07	8.93	8.36	89.31	88.82	3.00
609	47	T	2	494.66	495.08	8.27	8.51	60.24	60.02	0.00
610	47	T	3	506.31	512.95	9.21	9.08	71.92	71.64	0.00
611	47	T	2	440.43	442.91	7.97	8.74	53.43	53.27	4.00
612	7	T	1	454.29	453.47	6.56	6.13	67.05	66.55	1.75
613	7	T	2	442.64	445.09	8.33	8.56	60.99	60.78	0.00
614	7	T	2	434.65	436.31	7.93	9.29	50.16	50.03	5.67
615	7	T	3	515.74	516.57	8.75	10.17	82.46	82.05	0.00
616	39	T	2	469.48	467.41	10.14	10.36	74.33	74.10	4.50
617	39	T	1	444.64	443.81	7.35	6.94	66.33	65.94	5.75
618	39	T	3	424.32	425.55	8.26	8.20	64.58	64.32	4.25
619	39	T	2	453.27	452.04	8.20	7.91	69.00	68.68	4.75
620	10	T	2	485.83	487.49	7.41	7.14	61.44	61.11	0.00
621	10	T	2	481.51	481.51	6.81	6.38	64.18	63.73	0.00
622	10	T	3	474.65	478.31	8.38	7.99	73.72	73.37	3.88
623	10	T	1	465.54	462.27	4.42	4.35	67.66	66.66	3.50
624	10	T	2	461.29	459.66	6.65	6.21	69.50	68.97	6.73
625	3	T	1	502.57	500.88	6.65	6.99	55.67	65.38	5.50
626	3	T	2	528.16	530.24	8.95	8.17	71.99	68.07	5.03
627	3	T	1	580.35	579.49	7.62	8.63	62.97	68.96	4.50
628	3	T	2	500.89	507.94	9.25	8.59	78.36	73.37	0.00
629	3	T	2	452.51	455.04	8.36	8.89	71.61	74.11	0.00
630	3	T	2	538.02	536.36	9.15	8.16	74.71	62.90	0.00
631	18	T	1	433.17	434.84	5.86	5.70	57.09	65.38	6.96
632	18	T	2	463.13	459.80	9.00	7.93	69.91	61.55	0.00
633	18	T	1	455.72	447.76	5.59	5.13	55.61	56.51	5.26
634	18	T	2	416.62	417.87	6.59	6.40	64.10	62.87	7.81
635	18	T	3	439.75	439.54	8.08	8.43	64.59	65.29	0.00
636	18	T	2	464.12	471.48	8.35	7.09	65.36	65.73	6.00
637	18	T	3	449.45	448.05	8.99	6.88	61.88	61.69	5.93
638	16	T	1	521.60	519.95	5.96	5.33	63.83	65.60	8.40
639	16	T	2	570.88	569.48	6.43	5.92	69.88	65.64	3.25
640	16	T	2	490.71	491.55	6.74	5.87	64.96	66.45	0.00
641	36	T	2	411.93	412.34	9.36	9.00	78.23	77.89	2.25
642	36	T	3	435.58	439.26	8.80	8.38	77.20	76.85	2.46

643	36	T	3	427.94	431.62	9.38	9.09	77.26	76.95	3.00
644	36	T	1	450.22	443.31	6.33	6.25	49.76	49.50	4.26
645	36	T	2	421.34	420.53	6.18	5.80	58.75	58.33	0.00
646	36	T	2	434.12	435.34	6.53	6.38	52.60	52.31	2.50
647	36	T	2	478.19	476.96	9.29	8.85	81.03	80.67	0.00
648	38	T	1	438.19	437.36	3.92	3.73	51.31	50.50	8.96
649	38	T	1	466.52	466.10	6.08	5.68	59.24	58.77	6.31
650	38	T	2	496.26	495.84	7.44	6.96	79.11	78.55	0.00
651	38	T	2	510.48	510.48	7.43	8.05	75.94	77.23	3.50
652	9	T	2	471.90	472.31	5.90	5.51	64.35	63.79	0.00
653	9	T	1	453.64	455.67	5.45	5.11	51.74	51.31	0.00
654	35	T	1	426.00	429.32	7.18	6.85	61.84	61.49	5.53
655	35	T	2	478.17	479.00	7.94	8.10	58.20	57.97	5.00
656	35	T	1	463.49	461.86	8.01	7.65	69.39	69.04	2.50
657	35	T	2	454.79	455.61	7.39	8.72	46.97	46.85	9.06
658	35	T	3	436.17	440.27	8.24	7.83	73.08	72.72	4.00
659	35	T	3	446.94	447.37	10.27	9.94	83.42	83.09	0.00
660	48	T	1	479.69	479.29	6.10	5.70	60.41	59.95	7.75
661	48	T	3	479.67	480.49	9.93	9.56	83.90	83.58	2.50
662	48	T	2	480.32	479.91	8.65	8.57	67.62	67.35	4.25
663	48	T	3	487.96	488.79	9.68	9.96	81.13	81.70	0.00
664	48	T	3	470.76	469.13	9.47	9.13	79.98	79.66	0.00
665	34	T	1	413.33	414.57	6.85	7.43	55.01	57.53	4.00
666	34	T	2	436.94	436.94	8.28	8.09	66.63	66.34	3.00
667	34	T	2	411.98	411.16	7.12	7.13	54.37	54.12	2.75
668	34	T	1	414.15	412.92	6.18	5.90	52.88	52.53	3.00
669	30	T	2	413.33	412.10	8.23	9.35	62.78	64.02	2.75
670	30	T	1	392.50	390.11	6.19	6.16	47.94	47.69	2.75
671	30	T	1	398.20	395.74	6.10	5.80	53.63	53.27	0.00
672	30	T	2	427.73	431.41	8.36	8.38	63.79	63.55	1.25
673	28	T	2	470.20	465.99	8.54	8.97	68.08	76.25	2.75
674	28	T	1	448.10	446.01	8.79	8.79	63.95	63.95	2.25
675	28	T	1	427.95	431.17	7.75	8.05	59.53	61.16	1.95
676	28	T	2	471.37	474.88	8.78	8.80	61.39	65.83	0.00
677	46	T	2	410.36	414.10	8.62	10.24	54.02	53.90	0.00
678	46	T	1	419.69	415.63	6.40	6.16	53.35	53.03	0.00
679	46	T	2	446.32	444.26	8.81	8.32	79.52	79.12	0.00
680	11	B	2	450.11	450.99	8.09	8.09	78.71	78.71	2.15
681	11	B	3	457.83	461.60	9.65	9.32	65.37	61.29	0.00
682	11	B	1	456.62	454.81	5.97	5.91	56.69	63.95	8.39
683	11	B	2	550.87	534.65	6.79	8.33	67.75	86.23	3.50
684	11	B	2	540.03	545.89	11.11	11.27	78.80	80.13	0.00
685	11	B	3	512.67	521.33	10.46	10.04	90.79	78.11	0.00
686	11	B	2	473.72	478.61	11.24	11.42	84.21	87.13	0.00
687	11	B	3	581.85	551.22	10.15	8.98	91.52	80.22	0.00
688	11	B	3	531.11	527.74	10.30	8.96	85.71	68.99	0.00
689	43	B	2	447.64	448.04	7.10	6.94	56.77	56.48	0.00
690	43	B	3	519.68	523.03	11.50	10.09	91.97	90.22	3.00
691	43	B	1	460.41	458.75	6.23	6.26	46.72	46.47	6.50
692	43	B	1	541.08	538.13	6.53	6.54	57.46	59.13	6.25

693	43	B	2	465.83	466.66	8.90	8.88	61.57	60.73	2.75
694	43	B	3	490.97	496.31	9.50	9.57	71.98	71.74	3.75
695	43	B	3	495.25	500.58	10.22	10.13	84.82	83.75	0.00
696	43	B	2	482.45	480.79	8.82	9.25	62.53	62.33	0.00
697	18	B	1	449.98	454.50	4.72	4.06	52.44	52.35	3.00
698	18	B	1	512.46	515.14	6.16	4.51	65.12	63.57	2.85
699	18	B	3	527.87	504.42	5.86	5.30	62.31	71.37	0.00
700	18	B	4	551.14	549.33	6.78	5.60	77.38	65.35	0.00
701	18	B	2	468.32	459.20	4.45	4.35	57.72	60.10	0.00
702	18	B	4	489.69	488.01	9.19	8.16	89.06	89.15	3.25
703	18	B	2	467.73	465.66	5.37	5.10	65.46	68.82	3.48
704	18	B	2	477.81	475.28	10.59	8.76	68.89	73.23	0.00
705	18	B	2	514.26	511.35	7.18	7.19	69.48	71.07	0.00
706	18	B	2	481.38	486.82	6.60	6.79	64.76	67.72	2.00
707	18	B	3	506.86	511.28	9.81	9.08	71.26	72.25	0.00
708	18	B	3	516.66	508.90	9.01	7.74	69.18	70.78	1.25
709	18	B	3	493.62	489.50	7.30	6.56	70.11	69.96	0.00
710	18	B	3	571.04	573.69	8.34	8.19	72.23	63.77	0.00
711	44	B	1	479.75	478.51	4.55	4.33	45.11	46.68	2.75
712	44	B	2	467.06	466.65	7.37	6.44	58.80	58.24	5.75
713	44	B	1	441.78	439.29	5.33	6.17	51.55	53.74	5.00
714	44	B	1	472.12	469.20	5.61	6.59	69.35	68.36	3.00
715	44	B	2	540.63	535.68	6.71	6.94	63.08	61.97	4.85
716	44	B	2	461.88	460.65	5.80	5.87	49.17	53.60	3.25
717	44	B	3	504.90	513.07	8.45	9.60	71.58	71.02	0.00
718	44	B	2	508.83	506.75	8.48	7.96	79.72	79.27	5.06
719	44	B	2	478.03	477.62	8.46	8.25	64.34	65.28	5.96
720	44	B	3	511.41	511.82	9.40	8.95	82.61	82.25	0.00
721	44	B	4	525.34	530.24	11.49	11.27	92.04	91.76	2.00
722	47	B	1	476.86	471.86	6.83	6.83	62.81	61.10	6.71
723	47	B	2	446.81	446.40	6.57	6.58	49.89	49.64	5.49
724	47	B	4	519.33	526.38	10.06	9.51	90.60	90.20	2.10
725	47	B	2	484.62	483.80	9.11	8.77	76.79	76.46	0.00
726	47	B	3	527.27	530.17	10.52	12.30	93.39	93.45	0.00
727	47	B	4	548.21	550.70	13.12	11.77	103.51	103.22	1.50
728	47	B	2	529.82	530.66	7.44	7.23	60.29	59.98	0.00
729	47	B	2	474.72	473.90	7.90	7.19	61.11	59.34	3.50
730	47	B	4	533.46	535.51	11.16	12.64	97.82	97.51	0.00
731	47	B	3	540.78	539.96	9.82	11.41	88.94	88.02	0.00
732	47	B	4	493.57	499.41	10.15	9.83	83.76	83.44	3.50
733	47	B	3	530.02	530.84	13.78	11.61	101.44	101.22	1.25
734	3	B	1	525.58	526.41	4.52	5.03	64.00	67.09	5.27
735	3	B	2	606.26	602.08	6.93	7.52	70.95	71.56	3.00
736	3	B	3	554.22	541.87	9.91	8.97	70.30	67.63	2.00
737	3	B	2	534.07	524.07	6.33	7.19	61.53	74.60	7.29
738	3	B	3	545.41	542.19	11.73	12.28	87.67	87.80	0.00
739	3	B	3	517.26	539.94	12.49	11.39	86.20	81.68	0.00
740	3	B	2	524.27	515.15	8.03	9.12	75.28	85.54	3.55
741	3	B	3	565.91	559.21	13.30	13.28	88.88	91.02	0.00
742	3	B	3	559.38	554.66	9.60	10.33	84.47	83.37	4.26

743	3	B	3	528.30	515.46	8.59	9.17	69.96	70.97	4.00
744	31	T	1	443.79	437.63	7.38	6.92	71.45	70.98	3.05
745	31	T	2	470.37	467.09	6.21	5.82	70.37	69.76	0.00
746	31	T	2	431.66	432.07	7.71	8.61	59.51	60.58	0.00
747	31	T	2	466.99	465.75	7.99	8.61	62.60	61.40	0.00
748	31	T	3	456.43	458.87	11.28	10.54	74.79	73.64	0.00
749	41	B	2	459.38	464.06	8.29	8.29	64.93	70.80	0.00
750	41	B	2	493.63	502.09	8.93	9.06	92.22	81.75	0.00
751	41	B	1	468.17	464.14	7.31	8.77	61.32	74.68	7.56
752	41	B	3	533.05	535.98	12.23	11.12	92.32	86.44	0.00
753	41	B	3	540.71	558.47	10.28	9.74	102.09	82.28	0.00
754	41	B	2	501.23	513.49	10.29	10.75	83.28	90.85	0.00
755	41	B	3	549.86	553.21	12.31	12.03	96.15	91.83	0.00
756	41	B	3	579.35	577.11	11.24	11.41	88.79	85.94	0.00
757	19	B	1	502.30	499.85	4.22	3.93	44.73	44.18	8.25
758	19	B	1	494.77	493.55	3.93	3.99	43.34	42.33	6.49
759	19	B	2	466.36	470.04	6.47	7.89	76.86	76.14	0.00
760	19	B	2	489.83	491.06	5.85	5.48	65.79	65.18	3.75
761	19	B	3	490.32	498.57	6.82	6.40	65.01	64.57	0.00
762	19	B	2	469.87	468.21	6.88	6.72	64.71	62.93	0.00
763	19	B	2	452.12	455.79	6.61	5.87	63.95	60.20	3.00
764	19	B	3	438.35	439.58	7.39	8.69	73.86	71.53	2.75
765	19	B	3	483.93	486.40	9.34	9.08	75.54	75.23	3.75
766	19	B	3	487.13	487.95	7.25	7.22	68.97	67.66	2.50
767	19	B	3	514.76	515.58	6.98	7.00	72.18	72.00	0.00
768	7	B	1	559.35	558.11	4.30	5.04	57.84	59.38	4.00
769	7	B	1	470.07	470.07	5.95	6.19	57.59	58.40	0.00
770	7	B	2	491.95	492.77	8.58	8.25	72.08	71.75	0.00
771	7	B	2	503.40	501.77	9.71	10.38	67.56	67.39	3.75
772	7	B	2	472.21	473.85	10.02	11.04	67.62	67.46	0.00
773	7	B	2	517.11	516.30	9.74	10.20	88.02	87.80	0.00
774	29	B	1	507.38	504.92	5.95	6.01	59.69	59.43	10.55
775	29	B	1	545.99	544.33	4.48	4.27	58.94	58.12	5.75
776	29	B	2	472.52	473.36	8.60	10.17	54.36	54.24	0.00
777	29	B	2	554.86	555.28	8.03	7.53	76.84	76.39	0.00
778	29	B	2	487.98	485.07	8.45	8.95	51.68	51.58	3.00
779	29	B	3	524.15	525.79	7.84	7.43	70.51	70.14	3.00
780	21	B	2	433.09	433.91	7.65	7.53	60.59	60.32	0.00
781	21	B	1	459.24	458.84	5.29	4.96	60.95	60.32	4.81
782	21	B	2	479.32	477.68	7.61	8.11	74.85	74.42	0.00
783	21	B	3	500.79	502.85	10.69	12.30	83.59	83.18	5.50
784	21	B	3	442.20	444.24	9.90	9.86	70.36	67.12	2.00
785	21	B	2	505.19	502.74	9.83	9.48	82.84	82.52	0.00
786	24	B	1	501.38	503.47	8.81	8.63	82.04	80.18	0.00
787	24	B	2	522.59	525.08	7.61	7.61	70.31	70.31	8.16
788	24	B	3	624.86	624.44	12.31	11.52	100.70	96.22	0.00
789	24	B	2	580.03	572.92	9.40	9.40	86.33	86.33	0.00
790	24	B	3	587.78	586.95	12.23	12.40	95.96	97.56	0.00
791	24	B	3	643.04	636.20	11.79	10.11	103.67	81.35	0.00
792	6	B	1	498.61	497.79	5.10	5.26	56.19	57.52	6.00

793	6	B	2	480.92	479.28	6.23	5.82	61.01	60.54	0.00
794	6	B	1	495.46	494.21	5.69	5.30	58.26	57.73	7.06
795	6	B	2	504.23	502.58	6.01	5.68	73.94	73.22	2.50
796	6	B	3	540.61	541.85	7.70	7.22	73.47	73.00	1.50
797	6	B	2	500.76	499.95	7.06	6.70	63.35	62.99	8.75
798	6	B	2	474.66	473.02	7.79	7.46	66.84	66.50	2.25
799	6	B	2	517.09	514.64	8.53	8.05	78.52	78.12	4.81
800	6	B	2	489.41	490.64	7.98	7.97	63.20	64.53	3.25
801	6	B	3	527.55	528.38	9.21	8.63	90.00	89.52	2.25
802	8	B	1	439.33	434.79	5.86	5.56	51.43	52.87	0.00
803	8	B	2	472.54	474.59	5.85	6.39	50.50	55.80	2.00
804	8	B	2	453.55	454.36	6.56	6.15	63.29	62.86	0.00
805	8	B	2	520.28	519.45	8.70	9.61	74.95	75.68	0.00
806	8	B	2	503.66	502.44	8.01	7.68	59.51	58.01	3.75
807	9	B	1	460.79	461.20	5.07	5.58	49.79	51.04	5.00
808	9	B	1	426.55	424.10	4.97	4.63	51.69	51.18	6.00
809	9	B	2	445.30	443.66	8.51	9.21	58.24	58.06	0.00
810	9	B	2	438.50	439.74	4.94	6.11	50.15	54.13	3.05
811	9	B	3	504.68	505.89	10.47	10.58	79.74	79.51	0.00
812	9	B	2	462.90	463.71	6.33	5.94	60.67	60.24	3.00
813	9	B	3	438.66	439.07	8.23	8.63	67.84	67.38	2.25
814	48	B	1	418.62	417.80	4.07	3.87	52.90	52.11	2.50
815	48	B	2	446.67	445.01	7.15	6.81	61.34	60.98	3.50
816	48	B	1	522.30	521.47	3.85	3.62	47.71	46.98	2.80
817	48	B	2	483.62	481.58	5.73	5.35	58.80	58.31	4.00
818	48	B	2	474.29	471.82	7.41	7.31	66.29	62.36	0.00
819	48	B	2	441.71	442.54	8.53	9.16	59.00	58.82	5.75
820	34	B	1	454.78	456.43	4.56	4.33	59.07	58.30	0.00
821	34	B	1	431.54	428.64	5.99	5.63	55.23	54.81	3.00
822	34	B	3	487.87	488.69	9.39	8.95	82.52	82.16	0.00
823	34	B	2	476.72	475.48	6.14	5.74	66.93	66.35	7.62
824	34	B	4	527.72	533.03	10.73	10.09	102.59	102.15	1.50
825	34	B	2	468.37	467.55	6.69	6.30	62.18	61.77	3.75
826	34	B	2	503.19	528.76	6.70	6.25	70.53	69.98	3.25
827	14	B	2	464.87	463.21	6.52	6.68	70.84	69.08	0.00
828	14	B	1	438.97	437.32	6.54	6.40	52.59	52.30	6.31
829	14	B	3	470.60	470.19	8.00	7.54	73.60	73.21	2.79
830	14	B	1	448.73	445.44	6.88	6.47	64.27	63.85	2.00
831	14	B	2	469.75	468.53	5.91	5.52	63.47	62.92	2.00
832	14	B	3	472.06	475.34	10.78	10.98	75.77	73.36	0.00
833	26	B	1	423.28	424.09	6.63	6.30	58.64	58.28	6.09
834	26	B	2	455.65	451.98	8.11	7.79	68.95	68.62	4.43
835	26	B	1	429.99	427.11	4.63	4.31	48.68	48.14	3.25
836	26	B	2	471.92	475.21	6.69	6.38	57.76	57.41	6.00
837	26	B	2	488.74	488.33	7.74	7.36	67.80	67.44	0.00
838	26	B	2	497.61	495.14	8.74	8.37	74.61	74.27	0.00
839	26	B	3	475.93	476.34	10.65	10.67	81.12	80.87	0.00
840	26	B	2	422.95	421.30	6.64	6.20	66.29	65.80	3.75
841	26	B	2	460.37	461.19	6.72	6.29	74.11	73.53	4.00
842	28	B	2	462.13	471.81	8.74	8.16	66.58	69.53	0.00

843	28	B	2	584.96	578.26	5.59	5.86	58.38	64.19	6.50
844	28	B	3	565.39	553.60	11.97	9.97	89.86	80.58	0.00
845	28	B	1	546.04	547.29	6.95	6.84	74.76	73.76	6.75
846	28	B	3	594.89	610.94	7.72	8.56	73.66	78.99	0.00
847	28	B	2	558.79	557.68	9.25	10.40	85.27	86.51	0.00
848	28	B	2	525.67	537.34	8.20	8.96	61.90	77.46	0.00
849	28	B	3	587.24	586.82	11.30	10.46	95.24	93.77	0.00
850	45	B	1	420.28	419.87	4.66	4.34	49.12	48.58	4.10
851	45	B	1	467.78	468.62	3.79	3.58	48.45	47.68	2.00
852	45	B	2	411.34	410.50	7.04	6.83	56.97	56.65	4.50
853	45	B	4	498.05	506.26	10.73	11.15	79.78	79.49	3.49
854	45	B	3	399.50	403.20	7.75	7.77	58.78	58.53	4.00
855	45	B	1	404.67	407.15	6.87	6.70	54.83	54.54	4.50
856	45	B	2	479.85	477.82	6.50	6.10	61.48	61.06	4.25
857	45	B	2	421.19	420.78	7.40	7.12	62.37	62.04	9.75
858	45	B	2	477.74	475.28	7.92	7.48	72.47	72.07	4.59
859	45	B	2	429.00	429.00	7.11	6.80	60.98	60.65	0.00
860	45	B	3	444.82	447.68	8.26	8.17	65.19	64.92	0.00
861	45	B	2	478.89	481.38	8.93	8.40	54.31	54.21	6.19
862	45	B	3	463.92	465.56	9.16	9.22	72.62	71.94	0.00
863	45	B	3	472.44	475.71	8.34	7.85	77.71	77.30	2.25
864	16	B	2	442.27	445.62	4.33	4.14	53.82	53.45	6.00
865	16	B	3	484.63	484.35	7.33	7.24	51.65	54.93	1.75
866	16	B	2	470.35	472.21	5.18	5.27	55.31	58.84	3.75
867	16	B	2	468.31	469.98	6.44	5.37	62.79	57.19	5.25
868	16	B	1	477.49	473.70	4.19	4.11	54.25	58.17	7.50
869	16	B	2	479.32	480.58	4.45	4.12	56.37	56.48	5.53
870	16	B	3	486.21	485.79	5.83	5.41	57.79	50.97	0.00
871	2	B	1	495.12	495.12	3.54	3.45	43.95	45.64	7.25
872	2	B	2	468.99	471.51	5.27	4.35	47.33	49.86	3.05
873	2	B	1	469.31	467.35	4.39	4.00	49.97	50.31	0.00
874	2	B	2	444.48	447.02	7.46	5.13	64.33	62.85	0.00
875	2	B	2	473.21	469.88	6.46	6.13	62.84	61.43	0.00
876	2	B	2	441.16	441.57	6.31	5.10	60.31	59.65	3.75
877	2	B	3	495.76	495.90	6.33	6.37	57.80	59.46	0.00
878	12	B	1	424.84	424.03	4.75	4.55	40.19	39.87	5.83
879	12	B	2	429.73	430.56	5.98	5.59	65.51	64.92	0.00
880	12	B	3	480.00	482.89	8.33	7.85	77.36	76.95	0.00
881	12	B	1	432.11	428.44	5.35	5.00	51.90	51.44	2.25
882	12	B	3	407.83	410.73	8.80	9.03	64.36	64.14	4.00
883	12	B	2	476.29	470.46	5.84	5.47	55.46	55.01	6.75
884	27	B	2	490.23	485.67	6.29	5.88	61.34	60.86	0.00
885	27	B	2	460.78	459.56	7.28	7.48	53.87	53.65	1.25
886	27	B	1	489.66	485.12	6.24	5.82	65.51	64.97	0.00
887	27	B	2	429.62	423.40	6.69	6.31	60.86	60.46	0.00
888	27	B	2	446.61	442.92	7.91	7.81	61.83	61.56	2.50
889	27	B	3	500.98	500.16	10.52	9.96	94.59	94.19	0.00
890	27	B	1	510.84	505.09	5.17	4.83	58.40	57.79	4.50
891	27	B	3	472.39	473.63	9.11	9.42	65.60	65.38	0.00
892	27	B	3	491.46	496.00	9.52	9.23	78.13	77.82	0.00

893	27	B	3	494.47	498.99	8.59	8.12	78.38	77.99	0.00
894	32	B	1	395.21	391.91	6.35	6.35	47.98	47.72	4.50
895	32	B	1	409.89	411.91	6.37	6.15	52.67	52.37	5.25
896	32	B	2	503.29	500.42	7.15	7.16	69.76	69.30	8.50
897	32	B	3	468.30	481.09	9.40	8.86	86.25	85.83	0.00
898	32	B	2	446.36	444.73	8.74	8.66	68.28	68.01	0.00
899	32	B	2	515.55	515.55	8.73	8.87	76.77	75.46	0.00
900	32	B	3	453.85	456.30	9.94	10.22	73.20	72.99	3.03
901	23	B	1	447.44	443.77	5.47	5.11	54.41	53.94	5.83
902	23	B	2	413.25	414.50	7.38	6.98	65.88	65.49	3.75
903	23	B	1	446.63	445.40	7.16	7.03	56.44	56.16	6.93
904	23	B	2	446.88	447.71	8.85	9.12	64.98	64.77	0.00
905	23	B	2	494.51	489.66	8.47	8.62	68.34	70.26	3.47
906	23	B	2	447.07	449.91	7.92	8.15	58.25	58.04	4.50
907	1	B	1	447.08	440.45	3.78	3.57	47.92	47.14	3.00
908	1	B	2	462.53	460.08	5.04	5.14	67.87	67.05	0.00
909	1	B	3	473.82	475.46	8.21	7.75	74.86	74.47	0.00
910	1	B	2	460.19	463.55	6.28	5.90	72.49	71.81	3.00
911	1	B	3	498.96	505.24	11.93	11.52	98.17	97.84	0.00
912	1	B	2	457.95	456.70	6.86	7.74	66.58	65.53	5.25
913	1	B	2	502.29	503.54	6.57	6.14	63.44	62.97	1.50
914	2	T	1	460.28	461.53	3.87	3.95	45.90	45.90	0.00
915	2	T	2	442.91	441.24	4.45	4.65	48.54	48.54	3.25

B = butt log; M = middle log; T = top log.

APPENDIX 2B: RESULTS OF COMPRESSION STRENGTH PARALLEL TO THE GRAIN FOR CLEARWOOD SPECIMENS FROM THE FIVE LOW AND FIVE HIGH STIFFNESS TREES: A and B represent matching specimens from the same board.

Sample No.	Tree No.	Group of trees based on Stiffness	Log type	Popsition relative to the pith	MOE (GPa) A	MOE (GPa) B	MCS (GPa) A	MCS (GPa) B
1	11	G3	T	2	7.48	7.48	32.69	32.82
2	11	G3	T	2	7.16	7.16	33.38	33.31
3	11	G3	T	1	6.87	6.87	23.88	23.38
4	11	G3	T	3	9.94	10.05	36.38	36.63
5	11	G3	T	2	8.67	8.67	31.71	32.29
6	24	G3	T	2	8.29	8.29	32.21	32.46
7	24	G3	T	1	6.01	6.01	27.57	28.80
8	24	G3	T	2	7.90	7.90	31.00	31.49
9	24	G3	T	3	11.71	11.70	44.55	44.92
10	24	G3	T	3	10.02	10.04	43.10	41.87
11	24	G3	T	2	8.30	8.30	35.29	34.68
12	41	G3	M	1	7.05	7.05	30.15	30.15
13	41	G3	M	1	6.98	6.98	28.17	27.92
14	41	G3	M	3	11.76	11.84	42.80	42.31
15	41	G3	M	2	9.82	9.82	31.97	33.46
16	41	G3	M	2	9.67	9.67	33.58	34.68
17	28	G3	M	1	5.88	6.00	26.68	24.35
18	28	G3	M	2	8.58	8.76	35.13	36.29
19	28	G3	M	3	11.23	10.18	42.61	41.64
20	28	G3	M	1	6.65	6.63	26.36	26.11
21	28	G3	M	3	9.70	9.82	39.75	38.37
22	28	G3	M	3	10.05	10.65	37.75	39.73
23	28	G3	M	2	11.03	10.75	37.36	37.54
24	25	G1	M	1	6.54	6.27	28.69	27.71
25	25	G1	M	2	7.88	7.59	32.69	30.35
26	25	G1	M	2	7.42	7.82	29.72	29.97
27	25	G1	M	3	9.41	9.50	39.21	39.88
28	25	G1	M	2	8.89	9.08	36.52	37.00
29	25	G1	M	2	7.57	8.26	34.35	30.35
30	16	G1	M	1	5.39	5.19	24.76	23.67
31	16	G1	M	2	6.16	5.39	29.90	31.03
32	16	G1	M	3	7.68	6.77	36.19	39.95
33	16	G1	M	2	7.05	6.32	26.82	26.84
34	16	G1	M	3	9.87	9.67	47.57	34.84
35	16	G1	M	2	8.88	7.57	35.02	29.77
36	5	G1	M	1	5.32	5.34	23.54	24.42
37	5	G1	M	2	6.47	6.45	28.13	27.63
38	5	G1	M	3	8.36	7.91	35.58	36.40
39	5	G1	M	3	9.27	10.47	32.25	40.90
40	5	G1	M	1	6.35	5.79	25.00	27.17
41	5	G1	M	2	5.98	6.50	26.97	31.46
42	5	G1	M	2	7.11	7.78	27.02	25.79

43	5	G1	M	2	8.16	7.61	27.91	27.11
44	5	G1	M	2	7.31	7.65	32.88	39.40
45	5	G1	M	2	8.47	11.25	26.34	33.96
46	5	G1	M	3	9.35	7.92	36.56	35.55
47	11	G3	M	1	6.88	6.55	39.44	24.64
48	11	G3	M	2	8.53	8.97	29.82	29.16
49	11	G3	M	2	10.03	9.51	36.67	36.44
50	11	G3	M	2	7.67	7.87	29.25	29.28
51	11	G3	M	3	10.35	9.61	40.20	37.25
52	11	G3	M	3	12.65	12.44	30.85	30.95
53	18	G1	M	1	5.49	5.59	26.79	22.04
54	18	G1	M	1	5.45	5.25	24.87	26.93
55	18	G1	M	3	11.07	9.49	38.07	35.68
56	18	G1	M	2	8.44	6.60	34.80	33.92
57	18	G1	M	3	9.76	8.41	37.41	34.32
58	18	G1	M	2	9.90	8.55	38.36	30.40
59	18	G1	M	4	11.88	9.28	37.44	37.61
60	18	G1	M	2	8.10	7.24	35.92	25.82
61	18	G1	M	3	6.36	6.14	41.11	38.17
62	24	G3	M	1	8.02	8.91	27.46	27.91
63	24	G3	M	2	9.42	9.65	34.90	35.66
64	24	G3	M	3	10.38	10.67	42.08	38.23
65	24	G3	M	3	11.00	9.90	43.16	44.65
66	24	G3	M	2	8.62	8.78	41.21	36.11
67	2	G1	M	1	5.82	4.11	24.65	23.99
68	2	G1	M	2	5.53	5.12	24.12	21.97
69	2	G1	M	2	5.93	5.28	24.00	23.68
70	3	G3	M	1	7.50	8.90	31.76	28.27
71	3	G3	M	2	11.28	10.21	32.90	35.38
72	3	G3	M	3	12.02	10.95	43.91	41.29
73	3	G3	M	1	4.85	5.86	25.45	30.90
74	3	G3	M	2	8.77	9.59	31.60	31.58
75	3	G3	M	2	11.04	10.18	33.76	33.19
76	3	G3	M	2	9.21	7.59	31.57	32.75
77	5	G1	B	1	4.12	4.12	24.58	22.75
78	5	G1	B	2	4.82	4.64	23.94	24.47
79	5	G1	B	3	7.83	6.05	36.51	35.55
80	5	G1	B	2	4.14	4.19	27.46	26.02
81	5	G1	B	2	4.46	4.72	26.30	26.78
82	5	G1	B	4	6.66	9.18	40.10	39.77
83	5	G1	B	3	6.76	7.30	30.81	34.29
84	5	G1	B	3	6.52	6.58	34.37	34.34
85	5	G1	B	3	7.02	6.58	33.92	32.46
86	5	G1	B	2	6.12	6.05	27.46	27.61
87	5	G1	B	3	5.53	6.85	32.36	27.64
88	5	G1	B	4	9.90	8.89	39.43	41.04
89	5	G1	B	2	5.59	5.20	26.78	26.50
90	25	G1	B	2	7.11	7.69	29.92	30.63
91	25	G1	B	2	9.32	8.28	34.58	35.85
92	25	G1	B	1	7.31	6.73	26.55	31.25

93	25	G1	B	2	7.87	7.49	32.25	28.34
94	25	G1	B	3	8.84	9.13	34.47	38.04
95	25	G1	B	2	9.18	9.87	32.55	32.45
96	25	G1	B	4	9.41	10.27	45.30	44.95
97	25	G1	B	3	9.88	9.84	40.77	37.00
98	25	G1	B	4	10.26	9.66	37.09	46.72
99	5	G1	T	1	5.70	5.78	24.13	23.48
100	5	G1	T	1	5.48	5.69	26.29	27.58
101	5	G1	T	2	7.60	6.88	28.33	29.68
102	5	G1	T	2	6.42	6.34	29.67	27.15
103	5	G1	T	2	8.75	8.56	30.70	29.75
104	5	G1	T	2	7.58	7.74	34.13	28.08
105	5	G1	T	3	7.10	7.52	30.55	29.97
106	5	G1	T	3	7.17	7.97	38.15	36.98
107	41	G3	T	1	6.55	6.55	27.40	26.68
108	41	G3	T	2	8.38	8.38	30.30	31.13
109	41	G3	T	3	11.18	11.20	42.23	43.13
110	41	G3	T	2	8.45	8.45	33.92	34.30
111	41	G3	T	2	8.54	8.54	32.38	33.48
112	25	G1	T	1	6.83	5.97	35.87	26.79
113	25	G1	T	2	8.26	7.98	32.10	35.13
114	25	G1	T	3	9.35	8.88	32.55	39.35
115	25	G1	T	2	8.28	7.50	32.36	32.28
116	25	G1	T	2	9.14	8.58	33.13	31.15
117	3	G3	T	1	6.65	6.99	29.42	29.55
118	3	G3	T	2	8.95	8.17	34.88	33.76
119	3	G3	T	1	7.62	8.63	27.30	34.89
120	3	G3	T	2	9.25	8.59	36.54	35.10
121	3	G3	T	2	8.36	8.89	35.68	34.04
122	3	G3	T	2	9.15	8.16	34.98	36.72
123	18	G1	T	1	5.86	5.70	25.80	24.43
124	18	G1	T	2	9.00	7.93	33.93	32.98
125	18	G1	T	1	5.59	5.13	26.08	23.07
126	18	G1	T	2	6.59	6.40	28.18	25.18
127	18	G1	T	3	8.08	8.43	26.39	28.03
128	18	G1	T	2	8.35	7.09	29.63	30.05
129	18	G1	T	3	8.99	6.88	27.47	30.45
130	16	G1	T	1	5.96	5.33	28.24	30.15
131	16	G1	T	2	6.43	5.92	33.42	31.46
132	16	G1	T	2	6.74	5.87	29.30	21.31
133	28	G3	T	2	8.54	8.97	30.25	32.53
134	28	G3	T	1	8.79	8.79	25.38	25.00
135	28	G3	T	1	7.75	8.05	25.81	23.99
136	28	G3	T	2	8.78	8.80	29.90	28.89
137	11	G3	B	2	8.09	8.09	29.08	30.66
138	11	G3	B	3	9.65	9.32	31.93	31.06
139	11	G3	B	1	5.97	5.91	26.93	25.08
140	11	G3	B	2	6.79	8.33	38.60	38.45
141	11	G3	B	2	11.11	11.27	41.86	47.14
142	11	G3	B	3	10.46	10.04	40.13	38.92

143	11	G3	B	2	11.24	11.42	26.86	30.93
144	11	G3	B	3	10.15	8.98	32.51	37.95
145	11	G3	B	3	10.30	8.96	40.05	39.17
146	18	G1	B	1	4.72	4.06	23.22	23.48
147	18	G1	B	1	6.16	4.51	26.63	27.32
148	18	G1	B	3	5.86	5.30	27.84	27.82
149	18	G1	B	4	6.78	5.60	38.78	38.88
150	18	G1	B	2	4.45	4.35	23.11	23.36
151	18	G1	B	4	9.19	8.16	38.51	36.69
152	18	G1	B	2	5.37	5.10	30.10	28.48
153	18	G1	B	2	10.59	8.76	33.21	34.52
154	18	G1	B	2	7.18	7.19	31.89	32.66
155	18	G1	B	2	6.60	6.79	29.37	30.71
156	18	G1	B	3	9.81	9.08	35.30	33.01
157	18	G1	B	3	9.01	7.74	36.85	33.71
158	18	G1	B	3	7.30	6.56	32.03	29.06
159	18	G1	B	3	8.34	8.19	33.04	38.12
160	3	G3	B	1	4.52	5.03	22.00	25.80
161	3	G3	B	2	6.93	7.52	32.49	32.49
162	3	G3	B	3	9.91	8.97	36.89	34.22
163	3	G3	B	2	6.33	7.19	28.98	26.85
164	3	G3	B	3	11.73	12.28	40.63	38.08
165	3	G3	B	3	12.49	11.39	35.97	42.68
166	3	G3	B	2	8.03	9.12	31.29	33.53
167	3	G3	B	3	13.30	13.28	39.87	41.61
168	3	G3	B	3	9.60	10.33	44.73	45.33
169	3	G3	B	3	8.59	9.17	39.31	34.97
170	41	G3	B	2	8.29	8.29	30.94	32.83
171	41	G3	B	2	8.93	9.06	43.70	33.25
172	41	G3	B	1	7.31	8.77	32.18	25.33
173	41	G3	B	3	12.23	11.12	45.30	45.15
174	41	G3	B	3	10.28	9.74	46.42	44.16
175	41	G3	B	2	10.29	10.75	32.23	31.29
176	41	G3	B	3	12.31	12.03	46.08	45.48
177	41	G3	B	3	11.24	11.41	42.42	39.59
178	24	G3	B	1	8.81	8.63	36.98	34.50
179	24	G3	B	2	7.61	7.61	31.99	30.12
180	24	G3	B	3	12.31	11.52	44.40	43.32
181	24	G3	B	2	9.40	9.40	38.69	38.27
182	24	G3	B	3	12.23	12.40	46.59	46.94
183	24	G3	B	3	11.79	10.11	44.80	42.99
184	28	G3	B	2	8.74	8.16	30.86	30.98
185	28	G3	B	2	5.59	5.86	32.36	29.42
186	28	G3	B	3	11.97	9.97	41.74	43.26
187	28	G3	B	1	6.95	6.84	30.60	32.38
188	28	G3	B	3	7.72	8.56	34.07	33.32
189	28	G3	B	2	9.25	10.40	39.78	38.05
190	28	G3	B	2	8.20	8.96	33.63	37.28
191	28	G3	B	3	11.30	10.46	38.74	41.69
192	16	G1	B	2	4.33	4.14	21.91	24.20

193	16	G1	B	3	7.33	7.24	25.03	25.68
194	16	G1	B	2	5.18	5.27	24.16	22.77
195	16	G1	B	2	6.44	5.37	28.02	28.99
196	16	G1	B	1	4.19	4.11	23.33	22.12
197	16	G1	B	2	4.45	4.12	29.35	29.09
198	16	G1	B	3	5.83	5.41	29.49	26.73
199	2	G1	B	1	3.54	3.45	19.12	16.71
200	2	G1	B	2	5.27	4.35	19.67	23.04
201	2	G1	B	1	4.39	4.00	20.88	21.66
202	2	G1	B	2	7.46	5.13	29.31	26.17
203	2	G1	B	2	6.46	6.13	28.03	27.70
204	2	G1	B	2	6.31	5.10	26.20	26.93
205	2	G1	B	3	6.33	6.37	28.03	27.80
206	2	G1	T	1	3.87	3.95	22.36	22.86
207	2	G1	T	2	4.45	4.65	25.70	24.95

B = butt log; M = middle log; T = top log.
G1 = low stiffness; G3 = high stiffness.

APPENDIX 2C: RESULTS OF MODULUS OF ELASTICITY, BENDING STRENGTH AND DENSITY FOR CLEARWOOD SPECIMENS FROM THE SHORT INTERNODAL TOP LOGS.

Sample No. 1	Growth Ring No.	Tree No.	Wood Type	DENSITY (kg/cu.m)	MOE (GPa)	MOR (MPa)
2	1	22	N	427.33	5.45	51.47
3	1	39	O	426.71	4.95	51.06
4	1	32	O	425.85	5.92	48.42
5	1	19	O	432.83	4.51	41.84
6	1	8	N	430.10	5.23	49.45
7	1	6	N	428.33	4.28	42.95
8	1	36	O	418.73	4.49	41.02
9	1	33	O	414.13	4.12	33.51
10	1	3	O	409.74	7.92	49.05
11	1	6	N	406.41	4.56	49.86
12	1	35	O	417.80	3.49	40.11
13	1	41	N	416.67	5.30	50.40
14	1	44	N	415.44	4.41	46.50
15	1	22	N	507.72	4.58	47.33
16	1	24	O	506.63	5.16	41.87
17	1	5	O	505.90	4.38	50.93
18	1	21	O	521.46	6.30	65.00
19	1	37	O	520.87	4.15	48.93
20	1	45	O	517.27	3.92	41.27
21	1	10	N	497.48	4.41	46.09
22	1	30	O	454.49	3.87	46.25
23	1	48	N	445.33	5.36	42.94
24	1	28	O	434.44	4.86	49.19
25	1	1	N	481.08	5.26	49.24
26	1	44	N	465.48	6.14	56.83
27	1	27	O	459.31	5.54	60.15
28	1	47	O	406.06	4.99	47.90
29	1	10	N	375.81	5.43	47.80
30	1	23	O	371.75	5.33	46.02
31	1	42	O	368.76	5.98	54.60
32	1	29	O	380.53	4.13	50.09
33	1	48	N	380.19	5.30	45.33
34	1	13	N	377.07	4.44	46.52
35	1	40	O	368.55	4.98	46.60
36	1	25	O	363.42	4.35	37.54
37	1	46	O	351.86	4.47	45.31
38	1	18	N	332.66	3.89	42.40
39	1	7	O	367.79	4.59	47.38
40	1	34	O	365.65	4.99	50.50
41	1	13	N	365.59	4.54	47.00
42	1	41	N	400.30	5.65	52.41
43	1	8	N	400.25	5.68	50.01
44	1	17	O	399.71	5.70	51.52
45	1	43	O	405.06	4.91	44.53

46	1	11	O	401.78	5.55	49.00
47	1	38	O	401.07	4.07	46.32
48	1	16	O	398.65	4.56	52.64
49	1	18	C	389.50	3.75	36.76
50	1	31	O	389.44	5.82	54.21
51	1	15	O	387.44	4.43	42.61
52	1	1	N	398.21	5.61	54.55
53	1	4	O	396.72	4.32	41.15
54	1	18	N	389.50	3.75	36.76
55	5	11	O	420.73	6.82	56.16
56	5	16	O	454.27	6.40	52.21
57	5	26	O	409.60	6.31	51.69
58	5	15	O	423.53	6.52	52.40
59	5	20	O	412.09	6.81	55.25
60	5	6	C	444.04	6.61	60.11
61	5	41	C	475.72	7.16	58.73
62	5	3	O	445.51	9.32	54.20
63	5	8	C	476.87	6.96	58.87
64	5	19	O	413.13	6.32	49.46
65	5	47	O	472.42	8.15	62.36
66	5	8	N	476.87	6.96	58.87
67	5	43	O	441.24	6.89	58.42
68	5	46	O	424.46	6.66	48.51
69	5	18	N	452.60	5.60	54.09
70	5	17	O	415.07	8.61	66.66
71	5	32	O	415.94	5.84	47.48
72	5	42	O	414.75	6.08	45.82
73	5	18	N	422.49	6.29	52.15
74	5	22	C	422.52	7.78	59.81
75	5	18	C	422.49	6.29	52.15
76	5	13	C	395.23	6.08	50.35
77	5	22	C	435.09	6.35	57.04
78	5	48	C	398.33	7.73	58.12
79	5	44	C	423.24	6.29	56.10
80	5	44	C	438.52	6.83	54.87
81	5	35	C	460.16	6.57	63.23
82	5	48	C	380.02	5.61	51.87
83	5	18	C	452.60	5.60	54.09
84	5	6	C	454.06	6.31	55.78
85	5	1	C	398.07	6.09	49.00
86	5	35	C	434.72	6.54	56.56
87	5	41	C	449.06	7.23	51.87
88	5	1	C	412.94	5.81	49.78
89	5	10	C	444.90	8.18	63.04
90	5	13	C	387.25	5.42	44.66
91	5	10	C	428.09	7.37	58.07
92	5	8	C	454.25	6.54	52.51
93	5	1	N	398.07	6.09	49.00
94	5	41	N	475.72	7.66	58.73
95	5	13	N	395.23	6.08	50.35

96	5	1	N	412.94	5.81	49.78
97	5	48	N	380.02	5.61	51.87
98	5	6	N	454.06	6.31	55.78
99	5	22	N	422.52	7.78	59.81
100	5	22	N	435.09	6.35	57.04
101	5	6	N	444.04	6.61	60.11
102	5	10	N	444.90	8.18	63.04
103	5	41	N	449.06	6.51	51.87
104	5	35	N	434.72	6.54	56.56
105	5	8	N	454.25	6.54	52.51
106	5	10	N	428.09	7.37	58.07
107	5	35	N	460.16	6.57	63.23
108	5	44	N	423.24	6.29	56.10
109	5	44	N	438.52	6.83	54.87
110	5	13	N	387.25	5.42	44.66
111	5	48	N	398.33	7.73	58.12
112	5	24	O	484.21	8.37	64.92
113	5	38	O	473.79	5.99	57.47
114	5	35	O	457.84	6.34	48.27
115	5	36	O	421.99	5.89	49.63
116	5	23	O	405.55	6.91	58.19
117	5	7	O	423.21	7.45	59.44
118	5	4	O	407.53	7.10	58.38
119	5	35	O	428.25	7.30	56.53
120	5	25	O	449.36	8.71	67.78
121	5	37	O	510.55	5.61	51.52
122	5	5	O	473.25	6.28	55.39
123	5	39	O	407.89	6.08	55.84
124	5	28	O	441.02	6.85	56.41
125	5	31	O	435.78	8.22	60.93
126	5	34	O	415.77	8.24	64.73
127	5	29	O	451.88	7.03	58.88
128	5	40	O	424.09	7.83	58.70
129	5	33	O	411.60	4.59	47.35
130	5	27	O	470.54	6.90	56.69
131	10	6	C	463.54	7.40	61.46
132	10	6	N	480.33	8.75	64.75
133	10	31	N	459.03	8.93	71.19
134	10	28	N	467.53	8.34	64.15
135	10	30	N	402.12	6.93	60.03
136	10	6	C	480.33	8.75	64.75
137	10	31	N	429.98	9.66	68.69
138	10	34	N	430.55	8.84	68.42
139	10	30	N	428.71	9.61	76.13
140	10	4	C	481.60	7.56	63.20
141	10	34	N	425.86	8.19	64.90
142	10	29	N	462.85	9.64	74.00
143	10	32	N	456.26	8.28	66.30
144	10	1	C	481.30	8.61	66.20
145	10	33	N	440.95	7.72	59.48

146	10	6	N	463.54	7.40	61.46
147	10	1	C	416.35	8.56	58.24
148	10	45	N	390.80	6.70	50.11
149	10	6	C	488.45	7.43	62.98
150	10	3	C	477.30	8.26	71.22
151	10	45	N	432.27	6.58	54.17
152	10	3	C	440.59	10.32	61.54
153	10	14	N	432.72	7.09	60.97
154	10	42	N	449.11	7.86	60.94
155	10	3	N	477.30	9.44	71.22
156	10	46	N	449.29	8.77	66.23
157	10	1	N	481.30	8.61	66.20
158	10	10	C	508.61	9.65	68.59
159	10	48	N	448.23	7.43	55.67
160	10	46	N	457.84	8.58	68.28
161	10	47	N	495.07	6.06	54.30
162	10	11	N	429.51	10.38	56.42
163	10	8	C	438.90	8.26	62.52
164	10	47	N	454.21	8.27	65.32
165	10	1	N	416.35	8.56	58.24
166	10	4	C	455.39	9.30	73.18
167	10	10	C	493.66	10.97	76.29
168	10	4	N	481.60	7.56	63.20
169	10	44	N	465.98	9.16	78.00
170	10	10	C	511.67	10.15	79.59
171	10	39	N	439.76	9.44	70.03
172	10	7	C	493.69	9.11	70.60
173	10	41	N	490.55	9.65	58.10
174	10	4	N	455.39	9.30	73.18
175	10	39	N	409.90	8.03	60.05
176	10	13	N	391.95	8.18	62.64
177	10	3	N	440.59	9.71	61.54
178	10	44	N	463.86	9.60	72.49
179	10	43	N	465.02	9.74	76.01
180	10	38	N	518.09	6.15	58.65
181	10	43	N	485.81	7.94	68.91
182	10	13	N	409.86	7.57	64.61
183	10	8	C	530.43	9.66	80.10
184	10	5	N	492.94	6.79	59.57
185	10	28	N	465.16	7.01	66.42
186	10	44	N	445.07	8.01	63.19
187	10	7	N	493.69	9.11	70.60
188	10	19	N	430.22	7.23	57.21
189	10	44	N	482.59	9.63	73.15
190	10	19	N	415.09	7.63	58.12
191	10	38	C	518.09	6.15	58.65
192	10	7	C	442.39	8.71	66.76
193	10	26	N	442.23	9.37	73.20
194	10	26	N	509.27	9.03	56.51
195	10	20	N	457.59	9.20	70.17

196	10	10	N	493.66	10.97	76.29
197	10	5	N	480.79	6.87	53.96
198	10	18	N	421.28	7.12	55.76
199	10	20	N	435.05	7.59	60.65
200	10	39	C	439.76	9.44	70.03
201	10	22	N	528.76	10.86	84.67
202	10	36	C	406.76	6.89	55.20
203	10	41	N	471.54	10.48	64.10
204	10	8	N	438.90	8.26	62.52
205	10	37	C	422.48	6.77	54.04
206	10	24	N	546.51	11.73	79.58
207	10	23	N	430.31	8.65	64.60
208	10	41	C	468.45	11.14	66.97
209	10	33	N	441.92	8.18	61.37
210	10	25	N	443.90	9.13	67.74
211	10	22	N	516.48	9.75	72.16
212	10	39	C	409.90	8.03	60.05
213	10	10	N	508.61	9.65	68.59
214	10	15	N	428.64	7.81	59.47
215	10	16	N	454.56	9.05	65.97
216	10	41	N	468.45	10.44	66.97
217	10	41	C	490.55	10.09	58.10
218	10	18	N	398.15	6.60	55.09
219	10	36	C	383.96	6.98	51.72
220	10	18	N	423.13	6.82	50.22
221	10	25	N	434.04	8.22	55.89
222	10	8	N	530.43	9.66	80.10
223	10	32	C	456.26	8.28	66.30
224	10	15	N	446.81	7.77	58.81
225	10	30	O	416.64	8.41	65.45
226	10	33	C	440.95	7.72	59.48
227	10	22	N	506.03	10.23	78.95
228	10	27	N	513.04	8.52	73.38
229	10	10	N	511.67	10.15	79.59
230	10	10	N	547.53	10.30	80.67
231	10	18	N	405.59	6.19	52.13
232	10	7	N	442.39	8.71	66.76
233	10	27	N	535.70	9.24	77.58
234	10	31	C	459.03	8.93	71.19
235	10	31	C	429.98	9.66	68.69
236	10	4	O	459.38	9.15	68.82
237	10	33	C	441.92	8.18	61.37
238	10	41	N	455.67	9.46	59.27
239	10	5	C	492.94	6.79	59.57
240	10	34	C	425.86	8.19	64.90
241	10	43	O	465.47	7.51	63.48
242	10	11	O	482.30	10.19	71.58
243	10	34	C	430.55	8.84	68.42
244	10	41	C	471.54	10.48	64.10
245	10	46	C	457.84	8.58	68.28

246	10	46	C	449.29	8.77	66.23
247	10	45	C	390.80	6.70	50.11
248	10	45	C	432.27	6.58	54.17
249	10	47	C	495.07	6.06	54.30
250	10	37	N	422.48	6.77	54.04
251	10	48	C	448.23	7.43	55.67
252	10	47	C	454.21	8.27	65.32
253	10	15	O	428.96	8.15	59.69
254	10	20	O	430.14	8.20	54.87
255	10	5	C	480.79	6.87	53.96
256	10	44	C	445.07	8.01	63.19
257	10	43	C	485.81	7.94	68.91
258	10	43	C	465.02	9.74	76.01
259	10	19	O	404.06	8.20	61.79
260	10	41	C	455.67	10.88	59.27
261	10	42	C	449.11	7.86	60.94
262	10	44	C	482.59	9.63	73.15
263	10	10	C	547.53	10.30	80.67
264	10	27	O	509.77	9.72	72.75
265	10	44	C	465.98	9.16	78.00
266	10	26	O	466.70	9.19	64.52
267	10	44	C	463.86	9.60	72.49
268	10	32	O	416.07	7.84	59.62
269	10	11	C	429.51	9.08	56.42
270	10	6	N	488.45	7.43	62.98
271	10	11	C	531.93	8.69	67.78
272	10	18	C	398.15	6.60	55.09
273	10	33	O	440.93	7.18	60.35
274	10	18	C	423.13	6.82	50.22
275	10	19	C	430.22	7.23	57.21
276	10	18	C	405.59	6.19	52.13
277	10	18	C	421.28	7.12	55.76
278	10	13	N	409.33	6.30	56.21
279	10	28	O	451.21	8.18	56.67
280	10	26	C	442.23	9.37	73.20
281	10	13	C	409.33	6.30	56.21
282	10	29	O	426.80	8.67	67.45
283	10	36	N	406.76	6.89	55.20
284	10	31	O	459.34	10.20	69.30
285	10	15	C	446.81	7.77	58.81
286	10	7	O	467.76	8.99	66.65
287	10	13	C	391.95	8.18	62.64
288	10	14	C	432.72	7.09	60.97
289	10	16	C	454.56	9.05	65.97
290	10	27	C	513.04	8.52	73.38
291	10	39	O	459.33	9.12	65.42
292	10	13	C	409.86	7.57	64.61
293	10	15	C	428.64	7.81	59.47
294	10	27	C	535.70	9.24	77.58
295	10	20	C	435.05	7.59	60.65

296	10	22	C	516.48	9.75	72.16
297	10	26	C	509.27	9.03	56.51
298	10	28	C	465.16	7.01	66.42
299	10	38	O	496.72	10.24	66.27
300	10	30	C	428.71	9.61	76.13
301	10	28	C	467.53	8.34	64.15
302	10	25	O	454.23	9.16	65.19
303	10	40	O	462.71	10.21	74.14
304	10	19	C	415.09	7.63	58.12
305	10	23	O	425.63	9.59	65.79
306	10	25	C	443.90	9.13	67.74
307	10	29	C	462.85	9.64	74.00
308	10	30	C	402.12	6.93	60.03
309	10	22	C	528.76	10.86	84.67
310	10	24	C	546.51	10.63	79.58
311	10	22	C	506.03	10.23	78.95
312	10	36	N	383.96	6.98	51.72
313	10	20	C	457.59	9.20	70.17
314	10	11	N	531.93	9.32	67.78
315	10	37	O	432.66	8.18	59.84
316	10	36	O	398.17	6.86	57.17
317	10	25	C	434.04	8.22	55.89
318	10	23	C	430.31	8.65	64.60
319	10	24	O	521.91	10.94	65.48
320	15	18	C	470.23	9.96	75.63
321	15	18	N	471.47	9.96	75.63

N = normal wood; O = opposite wood; C = compression wood.

APPENDIX 3: MEAN VALUES OF TREE VOLUME, MODULUS OF ELASTICITY, BENDING STRENGTH, TENSILE STRENGTH AND DENSITY FOR THE 48 TREES

Tree No.	Volume (cu.m)	Density* (cu.m)	MOE* (GPa)	MOR* (MPa)	UTS** (MPa)
1	0.37	452.29	7.40	63.74	17.57
2	0.32	455.40	5.13	55.07	16.62
3	0.45	528.00	8.98	72.04	19.79
4	0.41	459.77	8.43	67.04	19.04
5	0.57	510.91	6.86	66.62	18.98
6	0.49	485.53	7.33	67.92	20.6
7	0.40	480.85	8.12	66.40	19.01
8	0.34	473.75	7.63	63.71	19.67
9	0.34	458.76	6.98	58.96	15.14
10	0.48	475.20	8.12	70.77	14.86
11	0.39	471.78	8.94	71.13	19.77
12	0.33	422.75	7.22	57.31	14.92
13	0.46	444.05	7.97	66.87	17.99
14	0.38	471.42	7.10	64.77	16.25
15	0.48	468.18	8.47	67.46	20.75
16	0.39	489.73	6.11	62.38	11.74
17	0.34	450.30	7.59	62.01	18.36
18	0.60	475.03	7.26	66.57	18.55
19	0.54	468.12	7.14	64.01	13.77
20	0.48	474.27	9.02	70.66	21.62
21	0.35	447.59	8.22	65.21	24.29
22	0.35	480.97	7.63	65.59	24.4
23	0.36	451.61	8.08	63.10	18.95
24	0.38	524.16	9.46	78.99	21.56
25	0.42	463.67	8.38	68.60	16.03
26	0.47	456.94	7.90	66.95	17.39
27	0.52	465.97	8.06	64.33	19.38
28	0.44	507.20	8.77	72.46	19.99
29	0.43	486.88	7.97	63.85	18.3
30	0.39	435.70	7.92	64.56	20.42
31	0.40	473.33	8.66	71.17	22.73
32	0.39	441.05	8.09	62.03	18.31
33	0.52	451.20	8.06	63.82	20.51
34	0.38	451.94	7.50	65.10	17.3
35	0.46	468.65	8.39	68.62	22.05
36	0.44	450.71	8.19	67.23	17.44
37	0.45	501.68	8.18	68.69	18.02
38	0.37	470.90	7.11	64.32	19.69
39	0.39	463.79	8.51	68.18	21.4
40	0.36	456.97	7.86	62.66	16.93
41	0.36	497.45	9.41	80.04	18.52
42	0.38	456.63	8.00	63.18	18.01
43	0.39	472.57	8.64	67.10	17.17
44	0.46	470.73	7.46	68.04	18.44
45	0.58	441.31	7.43	61.91	17.12

46	0.40	455.72	7.77	62.04	19.57
47	0.52	495.54	9.29	73.61	17.38
48	0.35	462.81	7.47	66.96	16.3

*** Results from clearwood testing.**
**** Results from in-grade testing.**

APPENDIX 4: RANKING RESULTS FOR MODULUS OF ELASTICITY AND DENSITY OF THE IN-GRADE TIMBER: DATA FROM ALL LOG TYPES.

a) **Mean modulus of elasticity and ultimate tensile strength for the three groups of trees ranked according to stiffness.**

Group	# of trees	# of boards	MOE (GPa)	UTS (MPa)	Density (kg/cu.m)
Low stiffness trees	5	110	5.3 (0.6)	15.8 (3.3)	481 (17)
Medium Stiffness trees	38	708	6.9 (0.5)	18.8 (2.3)	468 (22)
High stiffness trees	5	97	8.0 (0.3)	19.4 (1.6)	508 (15)

Values in parentheses are standard deviation.

b) **Mean density, stiffness and tensile strength for the three groups of trees anked according to density.**

Group	# of trees	# of Boards	MOE (GPa)	UTS (MPa)	Density (kg/cu.m)
Low density	5	98	7.0 (0.4)	17.8 (1.0)	434 (10)
Medium density	38	712	6.8 (0.9)	18.6 (2.6)	473 (17)
High density	5	105	7.5 (0.8)	19.1 (1.6)	515 (9)

Figures in parenthesis are standard deviations.

APPENDIX 5: A COMPARISON BETWEEN THE MEAN COMPRESSION STRENGTH OF GRADED TIMBER AND CLEARWOOD

5.1 THE FIVE LOW STIFFNESS TREES

a) **The mean compression strength (MCS) on the basis of the three log types.**

Experiment	MCS (MPa) by Log type			All
	Top log	Middle log	Butt log	
I (Timber)	25.9	25.3	23.8	24.8
II (Clearwood)	29.3	31.4	30.2	30.4
Ratio	0.88	0.81	0.79	0.81

b) **The mean compression strength (MCS) on the basis of the four positions relative to the pith.**

Experiment	MCS (MPa) by position relative to the pith				All
	1	2	3	4	
I (Timber)	22.1	24.4	25.9	30.7	24.8
II (Clearwood)	25.0	29.2	34.0	40.2	30.4
Ratio	0.88	0.84	0.76	0.76	0.81

Values in parenthesis are number of samples.

5.2 THE FIVE HIGH STIFFNESS TREES

a) **The mean compression strength (MCS) on the basis of the three log types.**

Experiment	MCS (MPa) by Log type			All
	Top log	Middle log	Butt log	
I (Timber)	26.2	26.8	29.5	27.8
II (Clearwood)	32.8	34.2	37.6	34.8
Ratio	0.80	0.78	0.79	0.80

b) **The mean compression strength (MCS) on the basis of the four positions relative to the pith.**

Experiment	MCS (MPa) by position relative to the pith				All
	1	2	3	4	
I (Timber)	25.2	27.1	30.2	n/a	27.8
II (Clearwood)	28.2	33.6	40.5	n/a	34.8
Ratio	0.89	0.81	0.75	n/a	0.80

Values in parenthesis are number of samples; n/a = not available.

SECTION C: JOINTS

- Mechanical fasteners; nails, dowels, screws, ring and toothed plate connectors or punched metal plate fasteners
- Traditional and carpentry joints
- Cold-formed steel plate joints
- Glued joints

Section B follows closely Eurocode 5 Chapter 5 "Ultimate Limit States". A slide collection is currently being assembled and will be made available to complement the lectures. This is in two parts, comprising design and text illustrating the majority of figures in the lectures and a photographic set, illustrating good practice in various engineering applications such as joints, prefabrication, materials, repairs and so on.

WHAT NOW?

We now have an essential book for all who seek excellence in timber design. However, we believe a STEP promotional/marketing fund must be set up to drive home the opportunity we now have at our feet. Those companies that have yet to support STEP must now come to the fore for the benefit of the timber industry.

How best to promote the use of STEP is open to debate. One solution could be the appointment of a full time person, with secretarial support, to telephone, cajole or visit each of the 100 or so university/college departments which are the primary target. If necessary this needs to extend to providing bespoke timber lectures drawn from the STEP material and designed in conjunction with departmental staff to suit the needs of the particular course in question. How to win the co-operation of the timber industry as a whole and to overcome the fragmented and often unco-ordinated nature of the industry, in order to achieve the necessary promotion of STEP is a matter of some urgency. At no time does this become more evident than when industry wide issues arise, such as education on timber for example. This was very much in evidence during the first round of fund raising for STEP and will arise again during the dissemination/promotion campaign to come. Who should do this? Who should pay for it? Where should such things be discussed? Who should decide? The timber industry surely must improve its ability to mobilise itself when needs must. How to start though ... that is the question.

* *An abridged version of the paper presented at the IWSc 1995 conference at Bristol by Dr Luke Whale and Andrew Abbott*

STIFFNESS AND TENSILE STRENGTH VARIATION WITHIN AND BETWEEN RADIATA PINE TREES

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SIGNIFICANCE OF THIS RESEARCH

The significance of this research for the utilization of plantation grown timber is that:

1. It demonstrates that within trees, wood stiffness increases from the pith to the outer part of the log, but is relatively constant up the height of the tree.
2. A modest genetic selection of the stiffest 10% of all trees in a stand would produce timber in the future with about 30% more stiffness and appreciably less low grade material.

ABSTRACT

A study of Canterbury timber reveals large increases in both stiffness and strength on going from pith to cambium, whilst there is little difference in stiffness but a slight decline in strength between butt and top log. Superior trees are almost twice as stiff and strong as the poorest trees.

INTRODUCTION

Variations in wood quality of any species can be attributed to variations within a tree, between trees in a particular stand, between different growing sites and between different silvicultural regimes. These variations apply to both sawn timber and small clear specimens. In this paper variations both within and between trees of radiata pine at a single site are examined.

Small clear specimens

The physical properties of New Zealand grown radiata pine have been summarised by Cown *et al.* (1991). They found that wood density increased with distance from pith and decreased with increasing height up the stem. The density increased by 30 to 40% in the first 20 to 30 growth layers from the pith, while differences in basic density between the butt log and the top log averaged from 7 to 11%. Tracheid length increased from about 1.5 mm at the pith to around 4 mm in mature outerwood with a slight increase in the values at levels above breast height.

Walford (1985) examined the relationship of density, cambial age and ring width with modulus of elasticity, modulus of rupture and maximum crushing strength, using small clear specimens of radiata pine from throughout New Zealand. He observed an increase in mechanical properties with an increase in density and cambial age and a decrease in ring width. The same study revealed large regional variations with the poorest values being reported for a dry, stony site on the Canterbury Plains in the South Island.

Sawn timber

Anton (1979) in his study of 70 x 35 mm and 90 x 35 mm timber sawn from 13-year old thinnings from Myrtleford, Victoria in South Australia reported that approximately 50% of his samples fell below Utility Grade (F4). Similarly Walford (1994) documents low stiffness values for 90 x 45 mm timber sawn from a 25-year old stand in Kaingaroa Forest, North Island of New Zealand. He tested long and short lengths in tension, bending and compression. The mean stiffness value, for instance, of his long length specimens (i.e. 1720 mm in bending) was only 6.5 GPa (F4 Grade), and the mean modulus of rupture was 22.1 MPa.

Studies at the University of Canterbury (Addis Tsehaye, 1989; Addis Tsehaye *et al.* 1991, 1992) on 90 x 45 mm boxed-pith radiata pine from Nelson province in the South Island gave a mean value of 6.4 GPa for stiffness and 16.8 MPa for tensile strength (2.0 m span between grips). The grade outturn of the material yielded 20% F8, 51% F5 and 12% F4 and 17% of even lower grade. Docking out the knots and finger-jointing increased the mean tensile strength to 19.5 MPa but the modulus of elasticity remained almost the same at 6.7 GPa. The surprising feature is that this boxed-pith timber from Nelson is as stiff as that for the entire output for the 25-year old stand from Kaingaroa Forest examined by Walford (1994). Finally, Hadi (1992) observed a very low mean stiffness, 2.9 GPa, and modest tensile strength of 10.7 MPa for 90 x 45 mm boxed-pith timber cut from 7-year old thinnings from the Canterbury Plains.

Walford (1994) noted that the silvicultural treatments generally advocated (early thinning to waste and pruning of the butt log) mean that the most mature timber from the butt logs will be clearwood and destined for high value non-structural uses, while structural timber will have to come from the unpruned upper logs and the knotty corewood of the butt logs. The quality of structural wood will deteriorate, further compounded by the emphasis on harvesting the stands at an early age. The major redeeming feature of the New Zealand wood supply is that some 50% of all stands have not actually been managed under such regimes. Even so previous studies have drawn attention to the relatively low stiffness of radiata pine from older stands.

Previous work (Walford, 1985; Hadi, 1992) has shown that some of the least stiff timber in New Zealand comes from the drier, stonier sites on the Canterbury Plains. This study seeks to test and interpret timber properties from whole trees grown in such stands.

Young stand of radiata pine in the typical terrain of the Canterbury forests.

MATERIAL AND METHODS

Preparation of test samples

Forty eight trees from a 25-year old plantation on the Canterbury Plains near Dunsandel in the South Island of New Zealand were felled and cross-cut to give three 3.6 m logs. Each log was identified by tree number and log type (butt, middle and top log).

At the sawmill the logs were live-sawn to the pattern shown in Figure 1. This pattern gave a central cant and one, two or three 40 mm flitches on either side. The flitches were re-cut at the breast bench to yield timber of nominal dimensions 100 x 40 mm. In re-cutting the 100 mm wide cant, the object was to box the pith within a single 100 x 40 mm piece and cut further pieces of the same size symmetrically working out towards the cambium. In practice there was some pith wander and the pith was not always confined to a single board. Hence the number of pith-containing pieces within a single log varied from one to three. Typically each cant gave 3 - 5 boards depending on the diameter of the log. The position of every board was recorded relative to the pith and numbered from 1 to 4 as shown in Figure 1. A total of 915 boards from the 48 trees (144 logs) were filleted and air-dried to approximately 12% moisture content.

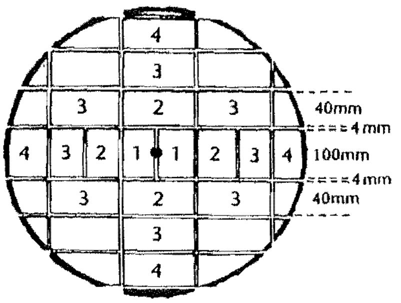

Figure 1. The live-sawing pattern generates a 100 mm thick central cant and 40 mm flitches off the sides. The pith may be confined to a single 100 x 40 mm rough-sawn board or it may wander across two (shown here) or even three boards.

After drying the boards were sent to Baigents Forest Industries Ltd. Nelson, where they were dressed to 90 x 35 mm and machine stress graded according to the Australian grading rules (Standards Association of Australia, 1978). The graded boards were returned and conditioned indoors for two months before testing. There was no need to reject the half dozen or so boards which were badly distorted after drying as the objective was to test destructively the boards in tension.

Mechanical testing

The modulus of elasticity of the boards was measured in flatwise bending by applying a static load of 2 kg at each third-point of a 3.3 m span. In the tensile test the boards were clamped with hydraulic pressure between 450 mm long jaws to give a free length of 2.6 metres. The tensile force was applied by a 200 kN capacity hydraulic ram controlled by a manually operated valve. A load cell measured the applied force. The modulus of elasticity in axial tension was determined under modest loads (< 35 kN), whereas the failure load ranged between 25 kN to 150 kN.

RESULTS

Grade distribution

The structural grade values used in this paper follow the Australian grading rules (Standards Association of Australia, 1988). A summary of the Australian basic working stresses for radiata pine structural grades in bending, tension and stiffness are presented in Table 1. (For a comparison with the UK BS 5268; Part 2, Strength Classes see Table 10.)

Table 1. Basic working stresses for radiata pine structural grades in bending and tension, and modulus of elasticity

Machine stressgrade	Bending (MPa)	Tension[1] parallel to the grain (MPa)	Modulus of elasticity (GPa)
F2	2.7	2.1	4.5
F3	3.4	2.6	5.2
F4	4.3	3.3	6.1
F5	5.5	4.1	6.9
F7	6.9	5.2	7.9
F8	8.6	6.6	9.1
F11	11.0	8.4	10.5

1 The tensile strength values, obtained by short-term testing and reported in this paper, need to be divided by 2.1 before comparing with those listed above in the grading rules.

The machine stress grade recoveries with respect to the log type and the position of the boards relative to the pith are summarised in Tables 2 and 3. For all the 915 test samples the grade of the board is the lowest recorded grade over the full length of the board.

Table 2. Machine stress grades of boards according to the log type

Log	Grade				Total
	F4	F5	F8	F11	
Top	27	171	23	—	221
Middle	33	195	66	1	295
Butt	72	227	90	10	399
Total	132	593	179	11	915

Table 3. Machine stress grades for boards at different positions from the pith

Position from the pith	Grade				Total
	F4	F5	F8	F11	
1	78	123	5	-	206
2	49	343	48	-	440
3	5	127	114	4	269
4	-	-	12	7	19
Total	132	593	179	11	915

Mean stiffness and tensile strength values

a. *Variation in mechanical properties with log type* (butt to top log)

The mean modulus of elasticity and ultimate tensile strength according to log type are presented in Table 4.

Table 4. Mean values for modulus of elasticity and ultimate tensile strength, based on the three log types

Log	N	MOE (GPa) in bending	MOE (GPa) in tension	UTS (MPa)
Top	221	6.7 (1.4)	6.6 (1.7)	15.2 (8.3)
Middle	295	7.0 (1.7)	7.0 (1.7)	17.9 (5.7)
Butt	399	6.8 (2.0)	6.8 (2.1)	20.9 (8.3)
Total	915	6.8 (1.8)	6.8 (1.9)	18.6 (7.3)

Values in parentheses are standard deviations.

b. *Variation across the diameter*

The mean modulus of elasticity and ultimate tensile strength values are shown in Table 5 for each position relative to the pith, with all log types aggregated.

Table 5. Mean values for modulus of elasticity and ultimate tensile strength, based on position relative to the pith

Position from pith	N	MOE (GPa) in bending	MOE (GPa) in tension	UTS (MPa)
1	206	4.9 (0.9)	5.0 (1.1)	13.5 (3.8)
2	440	6.7 (1.3)	6.7 (1.4)	17.8 (5.8)
3	250	8.5 (1.3)	8.5 (1.5)	23.2 (8.0)
4	19	9.3 (1.3)	9.5 (1.5)	29.1 (9.5)
Total	915	6.8 (1.8)	6.8 (1.9)	18.6 (7.3)

Values in parentheses are standard deviations.

Table 6 shows the same values for each position relative to the pith, segregated according to log type.

Table 6. Mean values for modulus of elasticity and ultimate tensile strength, based on position relative to the pith and sorted by log type

Log	Position from pith	N	MOE (GPa) in bending	MOE (GPa) in tension	UTS (MPa)
Top	1	58	5.2 (0.8)	5.3 (1.3)	11.9 (3.9)
Middle	1	65	5.1 (0.9)	5.2 (0.8)	14.2 (3.8)
Butt	1	83	4.5 (0.7)	4.5 (0.9)	14.2 (3.1)
Top	2	120	6.9 (1.1)	6.7 (1.2)	15.8 (5.3)
Middle	2	145	6.9 (1.3)	6.8 (1.3)	17.2 (4.5)
Butt	2	175	6.5 (1.5)	6.5 (1.6)	19.7 (1.6)
Top	3	43	8.2 (1.0)	8.2 (2.0)	18.0 (5.7)
Middle	3	83	8.7 (1.1)	8.6 (1.2)	21.8 (6.5)
Butt	3	124	8.4 (1.5)	8.5 (1.5)'	26.0 (8.4)
Middle	4	2	8.6	8.5	26.8
Butt	4	17	9.3 (1.3)	9.6 (1.5)	29.4 (10.0)
Total		915	6.8 (1.8)	6.8 (1.9)	18.6 (7.3)

Values in parentheses are standard deviations.

It can be seen from the above tables that both the modulus of elasticity and the tensile strength vary over the cross-section and along the stem. Table 7 shows the ratio between mean modulus of elasticity and mean ultimate tensile strength.

Table 7. Ratio of mean MOE to mean UTS

Log	Position relative to the pith 1	2	3	4
Top	444	422	45[illegible]	-
Middle	370	398	393	-
Butt	317	330	326	327

c. *Variation between trees*

Differences in the mean modulus of elasticity and ultimate tensile strength between the individual trees were examined by ranking the modulus of elasticity and tensile strength values of the 48 butt logs separately. The 17 boards at "position 4" (Table 5) are from the butt logs of only 11 trees, so these 17 boards were not included when the between-tree comparison was performed. The 48 trees were divided into three groups. Two groups represent the five low and five high extreme value trees, and a large third group represents the medium value trees. Rankings according to stiffness and tensile strength differ slightly from one another. Three of the five low stiffness trees were also amongst the five low strength trees, whereas only two of the five high stiffness trees also displayed high strength characteristics. The mean modulus of elasticity and ultimate tensile strength for all the three groups are summarised in Table 8.

Table 8. Mean modulus of elasticity and ultimate tensile strength for the three groups of trees ranked according to stiffness: data from the butt logs only

Group	No. of trees	No. of boards	MOE (GPa)	UTS (MPa)
Five least stiff trees (10%)	5	47	4.7 (0.3)	12.1 (3.4)
Medium stiffness trees (80%)	38	311	6.5 (0.8)	20.2 (2.7)
Five stiffest trees (10%)	5	41	8.4 (0.6)	25.7 (1.1)

Values in parentheses are standard deviation

The machine stress grade distributions for the three groups of trees are summarised in Table 9.

Table 9. Grade distribution for all boards from the butt logs, from trees grouped according to stiffness

Group	No. of trees	No. of boards	F4 (%)	F5 (%)	F8 (%)	F11 (%)
Five least stiff trees (10%)	5	47	38.3	51.1	10.6	0.0
Medium stiffness trees (80%)	38	311	16.7	59.8	22.8	0.7
Five stiffest stiffness (10%)	5	41	4.9	41.5	34.1	19.5

Discussion

As expected Tables 2 and 3 show poorer grades on going from the butt log to the top log, although the grade outturn for the butt log is more variable (with 18% F4 and below and 25% F8 and better). In the butt log there is more low stiffness timber in positions 1 and 2 and more high stiffness timber in positions 3 and 4.

Table 4 indicates that the mean value for the modulus of elasticity changes little in going from the butt log to the top log, whereas the mean tensile strength decreases steadily from the butt to the top log. Consequently the ratio of the modulus of elasticity to the tensile strength differs significantly between log types (Table 7).

The change in the mean stiffness values on going from the pith to the cambium is greatest between positions 1 and 2 (Tables 5 and 6). Moving from position 1 to 2, 2 to 3, and 3 to 4, the percentage increase in stiffness is 36%, 27% and 11% respectively. The change in the mean tensile strength value follows a similar pattern to that for the stiffness: the rate of change between positions 1 and 2 and positions 2 and 3 is 31%, and between positions 3 and 4, is 25%. The rates of change observed in both properties are in line with the observation of Bendetsen (1978) namely, "the rate of change in most properties is very rapid in the first few rings, the later rings gradually assume the character of mature wood".

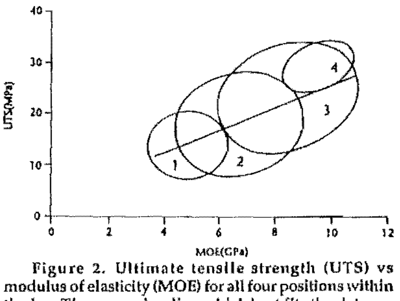

Figure 2. Ultimate tensile strength (UTS) vs modulus of elasticity (MOE) for all four positions within the log. The regression line which best fits the data,
UTS = 2.18 MOE + 3.68,
has a coefficient of determination, R^2, of only 0.32.

The general pattern of change for both the modulus of elasticity and tensile strength for the four positions across the radius is shown in Figure 2. The ellipses are centered at the mean values for the modulus of elasticity and ultimate tensile strength from Table 5, with 90% of all data points lying within each ellipse. A linear regression analysis performed between the modulus of elasticity and tensile strength values showed an R^2 value of 0.32 for the entire 915 boards. This value indicates that there is a very poor correlation between the modulus of elasticity and tensile strength, similar to the results of Anton (1979) who obtained an R^2 value of 0.36 between the modulus of elasticity and modulus of rupture in his study of 70 X 35 mm and 90 x 35 mm timber sawn from 13-year old thinnings of radiata pine. These values should not be directly compared with the R^2 value of 0.65 obtained by Walford (1982) in his study of 100 x 50 mm timber of radiata pine. He obtained this value by superimposing two completely different sample populations selected on the basis of density: the ranges of density being 269 kg/m^3 to 404 kg/m^3 for one batch, and 443 kg/m^3 to 456 kg/m^3 for the second. The poor correlation coefficients found in this study and the earlier work of Anton (1979) reflect the limited range of modulus of elasticity and strength values in these sample populations, due in part to the relative immaturity of the timber. This raises questions regarding the use of machine stress grading for such young timber. A further point arises in the choice of the appropriate regression equation as the ratio of the modulus of elasticity to the tensile strength increases up the tree, whereas at each level the ratio is essentially constant over the cross-section (Table 7).

The results for boxed-pith timber in the butt log (Table 6) are comparable to, but somewhat greater than, the results of Hadi (1992) who examined two hundred and twenty two 90 x 45 mm boxed-pith boards from a notionally similar stand on the Canterbury Plains. He found mean values of 2.9 GPa and 10.7 MPa for the modulus of elasticity and tensile strength respectively compared with 4.5 GPa and 14.2 MPa in this study. The present finding again confirms that boxed-pith radiata pine from the Canterbury Plains is inferior in stiffness compared with that of boxed-pith material from the Nelson region in New Zealand (Addis Tsehaye, 1989).

The surprising feature is that this timber from the Canterbury Plains has as good or better mechanical properties to similarly aged wood from Kaingaroa Forest selected as representative of the future wood supply (Walford, 1994). This is a curious finding because older trees from Kaingaroa forest have been the traditional bench mark for New Zealand timber. A re-evaluation of regional variations of wood properties may be needed now that the age of plantation forests has adjusted to the cessation of clear felling of much older stands and the age of clear felling settles at between 25 and 30 years. The general approach in wood quality studies has been to differentiate between regions on the basis of wood density. It is possible that this has obscured the fact that mechanical properties do not appear to be so largely affected.

Table 8 indicates the potential increase in stiffness and strength if one were able to select seedlings on the basis of such criteria at the time of planting. From the results for mean values shown in Table 8 it can be seen that there are large differences between the two extremes, i.e. the stiffest trees are almost 80% stiffer than the least stiff trees and the strongest trees are more than double the strength of the weakest trees. If one were to select trees having properties corresponding to those of the stiffest 10% of population rather than of the medium stiffness this would raise the quality of the timber by at least one grade. Table 9 indicates the grade recovery improvement with improving quality of material. The causes of such a variation in characteristics between trees within the same stand is the object of future investigation.

The traditional approach to improve wood quality has been to argue in favour of selection on the basis of density. This study and earlier ones have identified low stiffness to be the principal constraint to greater use of radiata pine for structural purposes. Thus, alternative strategies that approach the problem of low stiffness directly warrant investigation (Cave and Walker, 1994), bearing in mind that historically quoted values for the mechanical properties, and especially stiffness, of New Zealand radiata pine fall short of those for commercially important species of the Northern Hemisphere (Walford 1991).

CONCLUSION

The following conclusions are drawn from the present study:

1. The radiata pine timber from a stand near Dunsandel on the Canterbury Plains has low mean stiffness of 6.8 GPa;
2. Both the modulus of elasticity and tensile strength of radiata pine increase from the pith outwards. The changes between the first two positions near the pith ("positions 1 and 2") are especially large;
3. The mean modulus of elasticity is roughly constant up the height of the tree;
4. Tensile strength decreases steadily up the tree, i.e. from the butt log to the top log;
5. The ratio of modulus of elasticity to tensile strength changes systematically along the stem, and
6. The variation between trees is large enough to suggest that a modest selection programme could yield trees having at least 25% greater stiffness and strength compared to the mean values for the original population.

Table 10.

Basic Working Stress Australian Standard (AS 1720.1)			Basic Working Stress British Standard (BS 5268)		
Grade	Tension (MPa)	MOE (GPa)	Grade	Tension (MPa)	MOE (GPa)
F11	8.4	10.5	SC5	6.0	10.7
F8	6.6	9.1	SC4	4.5	9.9
F7	5.2	7.9	SC3	3.2	8.8
F5	4.1	6.9	SC2	2.5	8.0
F4	3.3	6.1	SC1	2.2	6.8

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REFERENCES

ANTON, A. (1979). The grading of 13-year-old radiata pine. Proceedings 19th Forest Products Conf., Melbourne, Paper 2/9.

ADDIS Tsehaye (1989). Proof testing of juvenile wood. M.For.Sc. thesis, University of Canterbury.

ADDIS Tsehaye, Buchanan, A.H. and Walker, J.C.F. (1991). Characterising boxedpith of *Pinus radiata*. J. Inst. of Wood Science 12 (4) 211-6.

ADDIS Tsehaye, Buchanan, A.H. and Walker, J.C.F. (1992). The strength of finger jointed boxed-pith timber of *Pinus radiata*. J. Inst. of Wood Science 12 (5) 285-9.

BENDTSEN, B.A. (1978). Properties of wood from improved and intensively managed trees. Forest Products Journal 28 (10) 61-72.

CAVE, I.D. and Walker, J.C.F. (1994). Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. Forest Products Journal 44 (5) 43-8.

COWN, D.J. McConchie, D.L. and Young, G.D. (1991). Radiata pine wood properties survey. FRI Bulletin No.50 (Revised), Forest Research Institute, Rotorua.

DANNY, W. (1988). Finger joint strength analysis of New Zealand radiata pine juvenile wood. M.For.Sc. thesis, University of Canterbury.

HADI, P. (1992). Proof testing of radiata pine boxed-pith timber. M.For.Sc. thesis, University of Canterbury.

Standards Association of Australia (1978). AS 1749: Rules for mechanical stress grading of timber. SAA, North Sydney

Standards Association of Australia (1988). AS 1720.1: Timber structures code, Part 1- Design methods. SAA, North Sydney.

WALFORD, G.B. (1982). Comparison of the tensile and bending strengths of 100 x 50 mm radiata pine. N.Z. Forest Service, FRI Bulletin No. 21.

WALFORD, G.B. (1985). The mechanical properties of New Zealand grown radiata pine for export to Australia. N.Z. Forest Service, FRI Bulletin No. 93.

WALFORD, G.B. (1991). Mechanical properties. *In* Kininmonth, J.A. and Whitehouse, L.J. *Properties and uses of New Zealand radiata pine. Volume one - wood properties, Chapter 8.* Forest Research Institute, Rotorua.

WALFORD, G.B. (1994). Preliminary results of juvenile radiata pine. Proceedings Pacific Timber Engineering Conf., Gold Coast, Australia. Vol. 2 725 - 30.

THE EFFECT OF MACERATION TIME ON THE PERCENTAGE OF BROKEN FIBRE PIECES IN BRITTLEHEART MATERIAL

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ABSTRACT

The effect of maceration time on the percentage of broken fibre pieces (PBFP) in brittleheart material of *Eucalyptus regnans* F. v. Muell. was investigated. Wood chips removed from one mature age and two young age *E. regnans* logs were macerated in glacial acetic acid-hydrogen peroxide mixtures for 5, 10, 15, 20 and 25 hours. The PBFP was determined for each sample after each five-hour period of maceration and microscopic observations of the whole and broken fibres noted. The median PBFP after five hours of maceration was 0.21 and it was observed that some fibres containing cell wall deformations had not yet broken. After 10 hours of maceration the median PBFP was 0.74 and most fibres containing cell wall deformations had broken into pieces with clean-cut ends at about 90° angle to fibre axis. Further maceration up to 15, 20 and 25 hours resulted in median PBFP values of 19.79, 58.59 and 96.58 respectively. At these longer periods of maceration, the number of broken fibres increased due to overmaceration causing whole fibres which did not contain cell wall deformations to break. It is suggested that in studies where broken fibres are used to identify or quantify the severity of brittleheart, preliminary work should be done to establish the time of maceration needed to cause fibres containing cell wall deformations to break while leaving fibres free of cell wall deformations intact. For *E. regnans* this time of maceration appears to be about 10 hours and it is anticipated that similar times would apply to other eucalypt species.

INTRODUCTION

Acid maceration of wood chips and the subsequent detection of broken fibres has proved an effective technique for the identification of brittleheart in eucalypts (Dadswell, 1958; Dadswell and Langlands, 1934 and 1938; Hillis *et al*, 1973). The presence of broken fibres in macerated samples has been directly linked to cell wall deformations found in the wood fibres prior

A COMPARISON OF DENSITY AND STIFFNESS FOR PREDICTING WOOD QUALITY OR DENSITY: THE LAZY MAN'S GUIDE TO WOOD QUALITY

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ABSTRACT

Traditionally density has been considered to be the most simple single indicator of wood quality, whether the wood is used as solid timber, for reconstituted panels or paper and board products.

This paper proposes that the quantity of structural timber could be significantly increased if trees were selected on the basis of wood stiffness rather than density. This proposal is based on tests of 915 boards from 48 trees from a 25-year-old radiata pine forest in Canterbury, New Zealand.

INTRODUCTION

Wood quality lies in the eye of the beholder. To the sawmiller, wood quality is reflected in the value of mill production and depends on grade outturn and value ($\$/m^3$) for each grade. To the structural engineer it is stiffness – most important for beams, joists, purlins; or strength – most important for studs and trusses.

With timber (as distinct from clearwood) variations in characteristic properties such as strength and stiffness have been attributed not only to differences in density, but also to the presence of spiral grain and natural defects such as knots.

Density has long been considered the best single index of intrinsic wood quality. In a frequently quoted article, Harris (1975) said:

> "One property widely used to assess the usefulness of wood for different purposes is its density. With any one species, timber of high density is stronger than timber of low density".

Harris et al. (1976) also deduced that a 10% increase in density could compensate for the expected strength reduction resulting from a 50 – 70% increase in knot size in the top logs of trees above the pruned butt log. The increased knot size arises from heavier branching in the live crown of lightly stocked stands, after pruning and thinning.

Concerning the improvement of wood quality, Harris et al. (1976) stated:

> "There is one final requirement needed to justify the economics of any programme to improve intrinsic wood properties: the improvement should be capable of recognition. Machine stress grading, or some similar non-destructive testing process, is essential if improvement in wood density are to be fully utilised and made profitable for the grower."

Harris and co-authors recognised that stiffness is a very important criterion for wood quality, but failed to draw the conclusion that breeding or selecting for stiffness might be preferred to that for density.

Rather than focusing solely on the *quantity* of matter in a piece of wood (its density), one might also consider the *quality* of the material in the cell wall (Cave and Walker, 1994).

Established relationships between density and clearwood properties are listed in Table 4.8 of the USDA Wood Handbook (USDA, 1987). The relationships are described by the following general equation:

$$S = K(D)^{n} \qquad [1]$$

where: S = clearwood property (MPa), D = density (kg/m^3), K = a proportionality constant differing for each property and N = an exponent for each property which defines the shape of the curve.

For example, according to the Wood Handbook the relationships for density with stiffness (MOE) and bending strength (MOR) are given by the following equations:

$$MOE\ (MPa) = 3.13 \times 10^{4} D^{0.9} \qquad [2]$$

$$MOR\ (MPa) = 2.56 \times 10^{2} D^{1.05} \qquad [3]$$

According to these equations, both properties of clearwood increase almost linearly with density. Thus a 10% increase in density only increases stiffness and strength by about 10%.

AN EXPERIMENTAL APPROACH

The value of density as a predictor of wood quality has to be assessed experimentally. Consider a study of 48 unpruned trees from a 25-year-old stand in the Canterbury Plains, New Zealand (Addis Tsehaye *et. al.*, 1995). These trees were milled to give 915 90x35 mm dressed, dried (12% M.C.), machine stress graded boards, 3.6 m long. Each board was identified according to log type (butt, middle, top), and distance from the pith (positions 1 to 4) as shown in Figure 1.

For each board the modulus of elasticity and tensile strength were measured by testing in tension to failure. Subsequently a clearwood sample adjacent to the failure zone was cut from each board and its unextracted air-dry density (12% M.C.) determined.

EFFECT OF POSITION FROM PITH

The general trends of increasing density, stiffness and strength observed in Table 1 are as expected, with all properties increasing with distance from pith.

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Table 1. Mean values of modulus of elasticity in tension (MOE), ultimate tensile strength (UTS) and clearwood density based on positions relative to the pith.

Position from Pith	N	MOE (GPa)	UTS (MPa)	Density (kg/m^3)
1	206	5.0 (1.1)	13.5 (3.8)	464 (44.7)
2	440	6.7 (1.4)	17.8 (5.8)	470 (42.2)
3	250	8.5 (1.5)	23.2 (8.0)	489 (38.4)
4	19	9.5 (1.5)	29.1 (9.5)	514 (38.8)
Total	915	6.8 (1.9)	18.6 (7.3)	475 (43.1)

Value in parentheses is a standard deviation.

The change in the mean density correlates with the changes in stiffness and strength. The increase from 464 kg/m^3 position 1 to 514 kg/m^3 at position 4 (i.e an increase of 11%) is less than the 30 to 40 percent increase in basic density on going from the first ring to 20 to 30 growth layers from the pith observed by Cown *et. al.* (1991). The smaller density differences in the current study between the innerwood (position 1) and outerwood (position 4) would follow naturally from the fact that the boards at position 1 include wood from the first 5-6 growth rings from the pith: thus the weighted average age of the boards from position 1 is around age 4 (with a corresponding higher density), depending on the precise location of the pith in each cross section. Furthermore, some of the wood in the vicinity of the pith (position 1) is infiltrated with resin.

VARIATION UP THE TREE

Table 2 shows variations by log height up the tree. An interesting feature is that the stiffness of the boards is indifferent to height in the tree whereas the strength varies systematically up the stem. The boards in the butt log are no stiffer on average than the boards in the top log.

Table 2. Mean values of modulus of elasticity (MOE), ultimate tensile strength (UTS) and clearwood density based on the three log types.

Log	N	MOE (GPa)	UTS (MPa)	Density (kg/m^3)
Top	221	6.6(1.7)	15.2(5.4)	462(44.2)
Middle	295	7.0 (1.7)	17.9(5.7)	462(37.7)
Butt	399	6.8 (2.1)	20.9 (8.3)	492(40.3)
Total	915	6.8 (1.9)	18.6 (7.3)	475(43.1)

Value in parentheses is a standard deviation.

The mean density variation between logs (Table 2) shows that there is a 6.5% difference between the butt logs and the top logs. This value is close to the 7% to 11% range obtained by Cown *et al.* (1991). However, the similarity in the mean density values (i.e 462 kg/m^3) between the middle logs and the top logs is unforseen: the number of growth layers decreases with increasing height in the stem and a decrease in mean density might have been expected. The precise heights above the ground for the density measurements in this study are uncertain because they were taken adjacent to the point of failure in each of the 3.6 m long test specimens. The mean height above the ground to the point of failure for the top log, middle log and butt log would approximately be 9.0 m, 5.4 m and 1.8 m respectively. Cown and McConchie (1983a), in their study of density in samples collected from 10 trees of 12-year-old radiata pine from Kaingaroa Forest, observed a drop in the mean basic density of 20 kg/m^3 between the butt and 3 metre height up the stem followed by a decrease of about 10 kg/m^3 for every further 3 metre height increment to the apex. In further studies of density in samples collected from 10 trees of 24-year-old and 10 trees of 34-year-old radiata pine Cown and McConchie (1983b, 1984) observed a decrease in the mean basic density of 20-30 kg/m^3 for each 10-metre height to the apex.

RANKING OF TREES ACCORDING TO DENSITY

Ranking of trees according to density gives an indication of the potential benefits to future forests through breeding on the basis of density. Differences in the mean density between individual trees were examined by ranking the 48 butt logs according to density of the boards. The 48 trees were divided into three groups. Two groups representing the five lowest and five highest density trees respectively, and a large third group representing the medium density trees. Table 3 shows density, modulus of elasticity and ultimate tensile strength for each group. These groups were chosen because any future selection of superior material might well consider such extremes within populations, which are here taken as the upper and lower 10%.

Table 3. Mean density, stiffness and tensile strength for the three groups of trees: data from the butt log only.

Group	No. of trees	No. of boards	Density (kg/m^3)	MOE (GPa)	UTS (MPa)
Low density	5	42	450(5.4)	5.9(0.6)	18.0(1.0)
Medium density	38	315	489(20.4)	6.6(1.1)	20.0(4.3)
High density	5	42	542(14.5)	6.8(1.7)	20.4(4.5)

Value in parenthesis is a standard deviation.

Table 3 shows that by ranking trees on the basis of density only a modest increase in stiffness and tensile strength (i.e 16% and 14% respectively) between the low density trees and the high density trees is achieved with no significant difference between the medium and high density trees. This is roughly in line with what one would expect from the USDA Wood Handbook equations (equations 2 and 3.)

The machine stress grade outturn of all the 915 boards is summarised in Table 4 and this can be compared with the machine grade distributions for the three groups of trees in Table 5. The machine grade values were obtained from a commercial stress grading machine operating according to the Australian grading rules (Standards Association of Australia, 1988). Again, the ranking and selection of superior trees on the basis of density would yield only modest gains.

Table 4. Machine stress grade outturn of all the 915 boards.

All boards	F4	F5	F8	F11
915	132	593	179	11

Table 5. Grade distribution for all the boards from the butt log, from trees ranked according to density.

Group	No. of trees	No. of boards	F4 (%)	F5 (%)	F8 (%)	F11 (%)
Low density	5	42	26.2	66.7	7.1	0.0
Medium density	38	315	16.5	56.2	25.4	1.9
High density	5	42	21.4	52.4	16.7	9.5

RANKING OF TREES ACCORDING TO THE STIFFNESS OF BOARDS

The 48 trees were ranked according to stiffness using the same method as described above. The mean density, stiffness and tensile strength for the three groups are summarised in Table 6, using data from the butt logs only.

Table 6. Mean density, stiffness and tensile strength for boards from the butt logs of the three groups of trees ranked according to stiffness (after Addis Tsehaye *et al.* 1995).

Group	No. of trees	No. of boards	Density (kg/m³)	MOE (GPa)	UTS (MPa)
Low stiffness	5	47	489(21.9)	4.7(0.3)	12.1(3.4)
Medium stiffness	38	311	486(26.8)	6.5(0.8)	20.2(2.7)
High stiffness	5	41	527(26.5)	8.4(0.6)	25.7(1.1)

Value in parenthesis is a standard deviation.

Table 6 indicates the potential increase in stiffness and strength if one were able to select seedlings on the basis of stiffness at the time of planting or thinning. From the mean values shown in Table 6 it can be seen that there are large differences between the two extremes i.e. the stiffest trees are almost 80% stiffer than the least stiff trees and the stiffest trees have more than double the strength of the least stiff trees. The medium stiffness trees are 40% stiffer and 67% stronger than the low stiffness trees, and 30% less stiff and 25% weaker than the high stiffness trees.

The machine stress grade distributions for the three groups of trees ranked according to stiffness are summarised in Table 7. The proportion of F4 and below is greatly reduced and the amount of F8 and above is increased in moving from the low stiffness group.

Table 7. Machine grade distribution for all the boards from the butt log, from trees ranked according to stiffness (after Addis Tsehaye *et al.* 1995).

Group	No. of trees	No. of boards	F4 (%)	F5 (%)	F8 (%)	F11 (%)
Low stiffness	5	47	38.3	51.1	10.6	0.0
Medium stiffness	38	311	16.7	59.8	22.8	0.7
High stiffness	5	41	4.9	41.5	34.1	19.5

This paper concentrates on selecting trees on the basis of the stiffness of the individual boards. There are two further steps in the analysis, moving down to clearwood properties and then to the intrinsic fibre characteristics at the ultrastructural level. Selection on the basis of the stiffness of small clear specimens cut from the same boards produces very similar results, as will be reported in a future paper. Moving down again to the ultrastructural level, it has been established for many years that density is a poor indicator of cell wall stiffness (Cave & Walker, 1994). We intend undertaking ultrastructural studies to identify the real determinants of ultrastructural and hence board stiffness.

RANKING OF TREES ACCORDING TO THE STRENGTH OF BOARDS

The mean values of tensile strength, modulus of elasticity and density for the five weakest trees, thirty eight medium strength trees and five strongest trees, ranked according to strength are summarised in Table 8:

Table 8. Mean ultimate tensile strength and modulus of elasticity for the three groups of trees ranked according to strength: data from the butt logs only.

Group	No. of trees	No. of boards	Density (kg/m³)	MOE (GPa)	UTS (MPa)
Weakest trees	5	49	496(27)	5.3(1.0)	11.3(3.4)
Medium strength trees	38	312	487(27)	6.5(1.0)	20.3(2.7)
Strongest trees	5	38	551(37)	7.7(0.9)	27.2(2.0)

Value in parentheses is a standard deviation.

As in the case of ranking according to stiffness, the strength of the strongest trees is more than double that for the weakest trees, but the strongest trees are only 45% stiffer than the weakest trees, compared with 80% when ranking by stiffness. The difference in stiffness between the weakest trees and the medium value trees is only 22%, and that between the strongest and medium value trees is only 18%, which are both lower than the respective 40% and 30% differences obtained when ranked according to stiffness. Tables 6 and 8 show that stiffness is a good indicator of strength, whereas strength is a less effective indicator of stiffness.

The machine stress grade distribution for the three groups of trees, ranked according to strength is summarised in Table 9.

Table 9. Grade distribution for all the boards from the butt logs, from trees ranked according to strength.

Group trees	No. of boards	No. of (%)	F4 (%)	F5 (%)	F8 (%)	F11
Weakest trees	5	49	24.5	44.9	26.5	4.1
Medium strength trees	38	312	17.3	60.9	20.8	1.0
Strongest trees	5	38	15.8	39.5	31.6	13.1

Table 9 indicates how the grade recovery improves with improving quality of material using strength as the determining criterion. As expected the grade recovery is good, but not as good as when ranking by stiffness.

DISCUSSION

Poor stiffness of radiata pine is of primary concern. Comparative studies between radiata pine and favoured timbers of the Northern Hemisphere indicate that the mechanical properties of radiata pine fall short of those for commercially important species of the Northern Hemisphere (Walford 1991): of the eleven species examined, radiata pine was ranked 7=/11 in strength and only 11/11 in stiffness.

Table 3 indicates only a modest improvement in stiffness and strength when ranking trees according to density, whereas in Table 6 the potential that would be achieved by ranking according to stiffness is much greater.

Similarly, Table 5 shows only a modest improvement in grade outturn when trees are ranked according to density, whereas the potential improvement by ranking according to stiffness is much greater (Table 7).

The traditional approach to improving wood quality has been to argue in favour of selection on the basis of density. The above results (Tables 3 and 5) show that density is not the best criterion for selecting high quality material. We question its value, for example, in selecting genetic material for future planting stock, or for selecting trees for thinning or utilization. Selection on the basis of stiffness has the potential for much greater increases in wood quality. This will be facilitated with some means of *in situ* stiffness measurement of trees or wood samples.

There are two underlying presumptions. First, that there is a good correlation between the stiffness of the lumber and the intrinsic quality of the wood. The second presumption is that it is possible to identify the superior trees of the future when examining seedlings or immature stands. The argument applies whether one is selecting for density, stiffness or some characteristic property at the fibre level. Invariably, any young tree producing high density juvenile wood (or other characteristic) will produce outerwood of greater density – it never produces outerwood of lower density. So if superior intrinsic characteristics are selected at an early age or in a breeding programme the improved characteristics will be observed in the mature outerwood.

CONCLUSIONS

From the current study the following conclusions can be drawn:

1. The general trend of increasing density from the pith to the cambium correlates with the changes in stiffness and tensile strength;

2. There is a significant difference in the mean density between the butt log and middle log and the butt log and top log;

3. There is a decrease in tensile strength from the butt log to the middle log to the top log, but no significant change in stiffness up the stem;

4. Ranking of trees according to density shows that density does not give a good prediction of machine stress grade. This conclusion is not unexpected, in that the grading criterion is stiffness;

5. Ranking of trees according to stiffness gives a superior grade outturn. If machine stress grading is to be used (as in structural engineering), then trees should be bred for stiffness, not density;

6. Some means of *in situ* stiffness measurement would be of great benefit,

(a) in young trees when deciding which trees to cull during thinning operations; and

(b) at the skids for making decision on log allocation to structural, utility, cut-stock mills or for pulp wood.

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REFERENCES

ADDIS TSEHAYE, A.H.BUCHANAN and J.C.F. WALKER (1995). Stiffness and tensile strength variation within and between radiata pine trees. Submitted to Journal of Inst. Wood Sci. (In Press).

CAVE, I.D and WALKER, J.C.F (1994). Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. Forest Products Journal 44(5): 43-8.

COWN, D.J. McCONCHIE, D.L. (1983a). Studies on the intrinsic properties of newcrop radiata pine I: Wood characteristic of 10 trees from a 12-year-old stand grown in Central North Island. FRI Bulletin No.36, Forest Research Institute, Rotorua.

COWN, D.J. McCONCHIE, D.L. (1983b). Studies on the intrinsic properties of newcrop radiata pine II: Wood characteristic of 10 trees from a 24-year-old stand grown in Central North Island. FRI Bulletin No.37, Forest Research Institute, Rotorua.

COWN, D.J. McCONCHIE, D.L. (1984). Studies on the intrinsic properties of new-crop radiata pine II: Wood characteristic of 10 trees from a 34-year-old stand grown in Central North Island. FRI Bulletin No.80, Forest Research Institute, Rotorua.

COWN, D.J. McCONCHIE, D.L. and YOUNG, G.D. (1991). Radiata pine wood properties survey. FRI Bulletin No. 50 (Revised), Forest Research Institute, Rotorua.

HARRIS, J.M. (1975). Better wood from better trees. What's New In Forest Research No.30. Forest Research Institute, Rotorua.

HARRIS, J.M, JAMES, R.N and COLLINS, M.J (1976). Case for improving wood density in radiata pine. New Zealand J. For. Sci. 5(3): 347-54.

Standards Association of Australia (1988). AS 1720.1: Timber structures code, Part 1- Design Methods. SAA, North Sydney.

USDA (1987). Wood Handbook: Wood and wood-based materials for engineers, architects and builders. Forest Products Lab., Forest Service, US Department of Agriculture. Hemisphere Publishing Corporation, New York.

WALFORD, G.B. 1991. Mechanical properties. *In* Kininmonth, J.A. & Whitehouse, L.J. Properties and uses of New Zealand radiata pine. Volume 1 – wood properties. Forest Research Institute, Rotorua.